Technical Report REMR-OM-25
September 1999

US Army Corps
of Engineers
Construction Engineering
Research Laboratory

REMR Management Systems—Flood Control Structures

Condition Rating Procedures for Earth and Rockfill Embankment Dams

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Prepared for Headquarters, U.S. Army Corps of Engineers

Repair, Evaluation, Maintenance, and Rehabilitation Research Program

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Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Civil Works Research Work Unit 32672

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Contents

Tables

Figures

Preface

The program documented herein was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Operations Management problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The work was performed under Civil Works Research Unit 32672, "Development of Uniform Evaluation Procedures/Condition Index for Civil Works Structures," for which Mr. Stuart D. Foltz was Principal Investigator. Mr. Harold Tohlen (CECW-O) was the REMR Technical Monitor for this study.

Dr. Tony Liu (CERD-C) was the REMR Coordinator at the Directorate of Research and Development, HQUSACE. Mr. Tohlen and Dr. Liu served as the REMR Overview Committee. William F. McCleese, U.S. Army Engineer Waterways Experiment Station (WES), was the REMR Program Manager. David T. McKay (FL-P), U.S. Army Construction Engineering Research Laboratory (CERL), was the Problem Area Leader for the Operations Management problem area.

This study was performed under the general supervision of Dr. Simon Kim, Chief, Maintenance Management Division (FL-P), Infrastructure Laboratory (FL) at CERL. The technical editor was Linda Wheatley, Information Technology Laboratory. Dr. Michael J. O'Connor was Director of CERL.

A draft version of this technical report was printed in September 1998. It was distributed within the Corps for review and comments. During this review, CECW-E requested that publication of the document and any related training be withheld until they could complete a more thorough review. Written comments were obtained from CECW-EG and two meetings were held at which more edits were discussed. These comments and suggested edits were incorporated as received. The first meeting was with CECW-ET, CECW-EG, CECW-OM in February 1999. The second meeting in September 1999 was with CECW-EG, some members of the Embankment Dam Condition Index (CI) development team, and additional Division/District representatives. The edits and changes are included in the current technical report. The CECW-EG has indicated that the changes do not adequately address all issues, but they have been unable to identify the additional issues with the specificity necessary to make any changes. This is at least in part due to perceived conflicts with a CECW-E approach for

incorporating risk assessment into the dam safety program that has yet to be developed.

As a technical report, this document is intended to be a summary of research results. The results include a product that can be used by Districts and others outside the Corps. Current Corps guidance on the use of CIs includes no references to embankment dams or flood control projects. At this time, therefore, each decision maker must individually determine if and how the Embankment Dam CI can assist in the management and safety of their embankment dams. Training workshops have been held in four districts with good to excellent results. Hydro Québec is implementing this CI for all their embankment dams. These activities indicate a previously unmet need that this tool helps to address. As with any research product, it may or may not adequately meet user needs in either the short or long term. Additionally, other tools and procedures developed in the future may prove preferable.

1 Introduction

1.1 Background

Over the past 100 years, the U.S. Army Corps of Engineers has designed and constructed numerous civil works structures, including flood control and hydropower projects. Many of these structures are nearing the end of their design life, yet service to the public must be maintained. The U.S. Army Corps of Engineers (USACE) Repair, Evaluation, Maintenance, and Rehabilitation (REMR) program was initiated to address issues related to maintaining these structures beyond their design life. One of the seven problem areas focuses on maintenance management and prioritization, including developing procedures to collect inspection data for monitoring condition of these structures.

For USACE civil works, the emphasis has been steadily shifting from construction of new facilities to maintenance and repair (M&R) of existing ones, so M&R has become an increasingly important part of the budget. In addition, USACE is one of many Federal agencies facing increasingly restrictive budgets and greater demands for budget justification. A prioritization system can be useful in the decision process for the management of existing facilities.

Being able to rely on the functionality and structural integrity of embankment dams as components of a flood control or hydropower project is essential. If embankment dam performance is not adequate, pool level may be restricted, causing power generation or recreation benefits to be lost, and, most importantly, putting downstream infrastructure and lives at increased risk.

1.2 Objective

The objective of this project was to develop a rating procedure that describes the current condition of embankment dams in a uniform manner. The project also produced a procedure for the prioritization of M&R activities on embankment dams. A condition index (CI) approach was adopted in a manner similar to other CI systems that have been developed by the U.S. Army Construction Engineering Research Laboratory (CERL). A system approach to condition assessment was adopted wherein complex considerations were treated in a systematic manner.

Throughout this project, it was maintained that the resulting procedure would be applicable to the ranking of current M&R activities that can be programmed and funded within a normal budgetary cycle. Although this process may be used to evaluate actions deemed too urgent to wait for the normal budget cycle, this methodology is not applicable to actions of an emergency nature.

There are a number of directly and indirectly related benefits for the embankment dam CI.

1. It is a good measure of changes in condition or performance over time. On a system level, this can tell managers whether long-term funding is adequate to maintain their facilities.

2. It assists engineers in evaluating the relative importance of existing deficiencies and prioritizing needs. It is not a detailed evaluation of dam safety nor does it replace criteria-based standards.

3. It can aid engineers when communicating with management regarding the importance and severity of deficiencies.

4. It assists prioritization of requirements for instrumentation and monitoring of dams.

5. It is a useful tool for assisting journeyman engineers in understanding how more experienced engineers make their evaluations.

1.3 Mode of Technology Transfer

Workshops have been held in four Corps Districts. The workshops include an overview and present the CI process by guiding the district engineers in the indexing of one or more of their dams. The focus on a single district and a project within the district adds relevance and increases interest of the participants. During review of this report, other workshops were delayed and it is expected that more districts will hold workshops. Software for REMR condition indexes is available at www.cecer.army.mil/fl/remr/remr.html.

It is recommended that the evaluation results of the embankment dam CI be incorporated into project documentation for periodic inspection reports as an appendix (Engineering Regulation (ER) 1110-2-100, *Periodic Inspection and*

Continuing Evaluation of Completed Civil Works Structures). See section 5.3 (p 52) for more information on implementation.

1.4 Overview

The initial conceptual ideas for the embankment dam CI project were developed during a Summer Faculty Fellowship Program in 1993 by Professor Glen R. Andersen at the U.S. Army Engineer Waterways Experiment Station (WES) under the supervision of Dr. Victor H. Torrey III. A 6-month feasibility study for the conceptual approach was then conducted by Professor Glen R. Andersen (formerly of Tulane University) with a subcontract to Professor Luc E. Chouinard of McGill University. This feasibility study was published as an engineering report by Tulane University (1995). Upon successful completion of the feasibility study, the full system development was initiated as a joint research project funded by CERL and Hydro-Québec through contract to Texas A&M University (Professor G.R. Andersen) and McGill University (Professor L.E. Chouinard), respectively. This full system development was funded for 2 years beginning in September 1995. The United States portion of the development was jointly administered by CERL and WES under the direction of Mr. Stuart Foltz and Dr. Victor H. Torrey III, respectively. The Canadian portion of the development was administered by the Sécurité des Barrages Section of Hydro-Québec under the direction of Mr. Jean-Guy Robichaud.

Participants (identified as expert or developmental panel in this report) in the full system development included Glen Andersen (Contractor, Texas A&M University), Luc Chouinard (Contractor, McGill University), Stuart Foltz (Project co-principal investigator, CERL), Dr.Victor H.Torrey III, P.E. (Project co-principal investigator, WES), Larry W. Franks, P.E. (Huntington District, CELRH), James H. Bradley, P.E. (Wilmington District, CESAW-retired), David P. Hammer, P.E. (Great Lakes and Ohio ~~Rivers~~ Division, CELRD-retired), Jean-Guy Robichaud, ing. (Sécurité des barrages, Hydro-Québec), Richard Gervais, ing. (Hydro-Québec, Baie Comeau), and Gaston Blanchette, ing. (Hydro-Québec, Chicoutimi). Other participants included Charles Bouvier and Fady Abdo, who were graduate students at Texas A&M University and McGill University, respectively.

2 Approach

The development of the embankment dam CI methodology required input from a panel of dam safety experts. This "expert panel" held a series of week-long meetings at locations in the United States and Canada. During these meetings, the experts were asked a series of structured questions that related their technical experience to various aspects of embankment dam M&R. These discussions were guided by the "interaction matrix" approach developed by Hudson (1992) following the cross-impact matrix analysis method developed by Gordon and Hayward (1968). During each expert panel meeting, embankment dams were inspected in order to validate the procedures that had been developed as of that date and to form a data base for a comparative exercise involving several dams. Three comparative exercises are included in Appendix A.

This report outlines the procedures and presents the rationale that were developed by the expert panel to assist in prioritization of M&R actions on embankment dams. Two separate methodologies are presented to assist in the prioritization of M&R tasks on embankment dams. One methodology incorporates defense groups (components designed to prevent various failure modes). The overall rating for the defense groups is also considered to be the CI of the dam. This procedure is fully described in Chapter 3. The second methodology incorporates the monitoring system (instrumentation and visual observation surfaces). Although it is not a formal part of the embankment dam CI, the rating system for monitoring devices is included in this report. At the level of detail that the CI procedure evaluates a dam, it is important to look at the condition and adequacy of the monitoring devices. Chapter 4 describes the procedure that results in a detection system CI in addition to the monitoring device priority rankings. The products of these two methodologies are prioritized deficiency lists, one for defense groups (Table 3.20) and another for monitoring devices (Table 4.6). These priority lists can later be incorporated into a broader management decision analysis framework by considering cost, scheduling, etc.

The approach for this CI was different than most other CIs in several ways. First, it includes no specific inspection procedure. Most CIs are based on a distinct inspection procedure, but it was felt that embankment dams are adequately inspected and additional value could not be provided by creating a

new inspection. Secondly, the CI process is less objective. The sub-component ratings are based on described ranges like for breakwaters and jetties, not specifc values as in other CIs. Additionally, unlike any other CI, the sub-component ratings are combined based on relative importances determined by the raters specifically for that dam. This is important in making the results relevent to the district concerns. The result has more subjectivity than other CIs, but it should still be consistent if the participants are knowledgable and honest. Spurious CI values can be identified as easily for this CI as for others. The CI procedure does provides some firm boundaries. McCann et al. (1985) discuss the importance of rational and consistent assessment:

> "The first step towards achieving consistency is use of a probablistic [absolute or relative] approach that provides a logical format.... A second step involves measures to insure consistency in applying a preliminary ... assessment procedure.... One of the reasons probabilistic methods are used so extensively ... is due to the fact that they provide an orderly, rational assessment of the events that could initiate a system failure."

Arguably, the strength of the embankment dam CI is in providing a framework for assessment. The third difference is that, during development, the focus quickly shifted away from the CI. The participants and others saw little benefit to having one number to relate the condition of a dam. They did not feel it could convey the complexity of the deficiencies that might be present on a dam. They were also concerned that the CI would be misunderstood to be a dam safety index. The participants were more interested in providing a tool that helped understand and prioritize engineering concerns for a dam. This resulted in a focus on priority rankings (see section 2.2). Note that the CI and priority rankings are based on exactly the same information, but the priority rankings communicate more detail.

Throughout this report, questions are posed that must be answered with numerical responses ranging from 0 to 100. The developmental panel considered that a precision of 10 on these responses represents an appropriate degree of resolution for the types of questions posed. The panel was concerned that, if relatively unlikely events were given weightings, there could be three negative effects. First, those events would tend to be overweighted. Secondly, consideration of the less likely events would needlessly increase the effort needed to complete the evaluation. Most importantly, it would divert attention from the most critical issues. On the other hand, some users may find benefit in using

higher resolution despite the inherent difficulty of accurately increasing the resolution. Possible benefits include (1) compiling a historical record of small problems that may gradually or suddenly become more severe and (2) allowing a quantitative priority ranking of small problems that require low cost repairs and may be justified on a cost-benefit basis.

This methodology is intended to be applied to individual embankment dams. For reservoir projects with multiple embankments, each embankment should be considered independently.

This system is intended to address embankment and spillway features, which have traditionally fallen under the purview of the geotechnical member(s) of the dam inspection team. However, the system also includes recognition of existing hydrologic and seismic criteria established by the Corps of Engineers Dam Safety Assurance Program (ER 1110-2-1155); ER 1110-2-1464 and ER 1110-8-2(FR) for the adequacy of existing spillway capacity; and ER 1110-2-1806 for seismic adequacy. Structural, electrical, and mechanical aspects of project operation are not covered in this system. This Technical Report is not intended to supersede any information, procedures, or policies within existing Engineering Regulations.

2.1 Definitions

Condition Index (CI) – A CI is a number between 0 and 100 based on a rating procedure that describes the current condition of a structure in a uniform manner. CIs are intended to be relatively objective measures based on Table 2.1.

Importance Factors – Most CIs are calculated using one of two methods. Either pre-determined "deduct values" are used for specific distresses such as in the CIs for concrete (see REMR-OM-4 and REMR-OM-16) or subcomponents are rated on a CI scale and weighted according to pre-determined importance and condition to calculate a component CI such as in the CIs for lock and dam gates (see REMR-OM-8, REMR-OM-13, REMR-OM-14, REMR-OM-17, and REMR-OM-18). The embankment dam CI uses the second method with one significant divergence from previous CIs. The weightings, termed "importance factors," are not pre-determined. The CI for embankment dams includes a structured process for the rating panel to determine dam-specific importance factors. This process increases the subjectivity of the CI, but consensus opinion was that the increased validity and accuracy of the results justified the increased subjectivity.

Table 2.1. U.S. Army Corps of Engineers REMR condition indexing scale.

Zone	Condition Index	Condition Description	Recommended Action
1	85 to 100	**Excellent:** No noticeable defects. Some aging or wear may be visible.	Immediate action is not required.
	70 to 84	**Good:** Only minor deterioration or defects are evident.	
2	55 to 69	**Fair:** Some deterioration or defects are evident, but function is not significantly affected.	Economic analysis of repair alternatives is recommended to determine appropriate action.
	40 to 54	**Marginal:** Moderate deterioration. Function is still adequate.	
3	25 to 39	**Poor:** Serious deterioration in at least some portions of the structure. Function is inadequate.	Detailed evaluation is required to determine the need for repair, rehabilitation, or reconstruction. Safety evaluation is recommended.
	10 to 24	**Very Poor:** Extensive deterioration. Barely functional.	
	0 to 9	**Failed:** No longer functions. General failure or complete failure of a major structural component.	

Priority Rankings – Priority rankings are a relatively new addition to the CI family of tools and products. Previously, a subjective priority ranking has been used with the CI for riverine rubble dikes and revetments (see REMR-OM-21). The priority rankings in the embankment CI are a product of the importance factors and condition ratings for a defense group or a monitoring device. They are intended to produce the highest ranking for the most important defense group or monitoring device in the worst condition. Further explanation and details are given in sections 2.2 and 2.4.

Prevention System – It is the system that prevents catastrophic failure of the dam. The defense groups act to control adverse conditions that might lead to one of the four identified failure modes.

Detection System – This system provides information about the ability of the dam to resist failure. Monitoring devices provide this information. It may also be referred to as the monitoring system.

Failure mode – Failure is the uncontrolled release of the reservoir. The four general failure modes identified for a dam are overtopping, erosion, piping, and mass movement (see Table 3.2).

Adverse Conditions – Adverse conditions are undesirable events occurring at specific locations on the dam that are associated with failure modes (e.g., piping of embankment materials). There are eight adverse conditions (see Table 3.3).

Defense Groups – An embankment dam is modeled as groups of components (defense groups) designed to prevent various failure modes (see Table 2.2).

Indicators – Indicators are used to assess the condition of a defense group. In the detection system, a subset of these indicators are evaluated according to their value in deducing the presence or absence of adverse conditions. Monitoring devices are rated based on their ability to provide information about indicators.

Changes in Geometry – This detection system indicator is sub-divided based on the location on the dam. It is a collection of various defense group indicators that are visible on the observation surfaces. They include:

- Differential movement (e.g., cracking, shallow slides, bulging, between fixed and floating structures)
- Loss of surface protection materials (Downstream Slope)
- Ruts and gullies (erosion into protected soil) (Downstream Slope)
- Degradation / breakdown of slope protection (Upstream Slope)
- Removal of bedding or protected material without the loss of outer slope protection (Upstream Slope)
- Loss of slope protection material (Upstream Slope)
- Sinkholes / depressions
- Surface grades
- Depth of erosion below protection.

Known Defect – A defense group may have weaknesses that do not currently impact the performance of the indicators significantly. These defects are nonetheless important. For this reason, an additional indicator — known defect — has been added for defense groups. Examples of known defects for pressure control in the foundation could be: a leaking diaphragm cutoff wall; an upstream blanket that does not extend far enough upstream; or a toe drain filter that does not meet present filter criteria. One known defect, "Pipeable material without a designed filter system," can significantly impact the CI of the defense group.

Table 2.2. Potential defense groups for embankment dams.

Defense Group	Components
Spillway Capacity	Sill, inlet channel, outlet channel
Spillway Erosion Control	Sill and main channel

Crest Elevation	Top of dam
Surface Runoff Collection Discharge System	Ditches, surface drains, etc.
Downstream Slope Protection	Stone, vegetation cover, etc.
Upstream Slope Protection	Stone, soil cement, etc.
Filtering in Embankment	Engineered filter materials to prevent the migration of finer soils
Pressure Control in Embankment	Chimney drains, blanket drains, finger drains, impervious core, etc.
Filtering in Foundation	Engineered filter materials to prevent the migration of finer soils
Pressure Control in Foundation	Relief wells, toe drain, cutoff wall, upstream impervious blanket, etc.

2.2 Priority Ranking of Defense Groups

An embankment dam is modeled as groups of components (defense groups) designed to defend against potential failure (uncontrolled release of the reservoir) by modes defined by the International Commission on Large Dams (ICOLD 1983). Table 2.2 presents potential defense groups for embankment dams.

The priority ranking ($PR_{DG\,i,j}$) of the i^{th} defense group of the j^{th} dam is formed as the product of three numbers: (1) a dam consequences factor (representing the consequances of failure of the dam), (2) a defense group importance factor (representing the importance of the defense group relative to other defense groups on a given dam), and (3) a defense group condition factor (representing the ability of the defense group to function in its particular role) in accordance with Equation 2.1:

$$PR_{DG\,i,j} = CF_{Dam\,j} \bullet I_{DG\,i,j} \bullet \frac{\left(100 - CI_{DG\,i,j}\right)}{100} \qquad \text{(Eq 2.1)}$$

$CF_{Dam\,j}$ = the relative importance of *Dam j* within the USACE inventory (based on consequences of failure)

$I_{DG\,i,j}$ = the importance of i^{th} defense group on *Dam j* and ranges from 0 to 1.0 such that the sum of all defense group importance factors for a particular dam is 1.0

$CI_{DG\,i,j}$ = the condition index of the i^{th} defense group on *Dam j* and ranges from 0 to 100 representing the ability of the defense group to function.

Priority rankings for each of the defense groups in accordance with Equation 2.1 will provide a means for the direct comparison and prioritization of M&R tasks among projects in an organization. The priority ranking expressed in Equation 2.1 will favor the most important defense groups on the most important dams that are in the worst condition. In the allocation of resources, other factors might be considered such as scheduling, funding constraints, minimum acceptable levels of condition, rates of deterioration, and cost and effectiveness of repair.

The set up of the priority ranking system for a given dam (i.e., evaluation of Equation 2.1) must be carried out by technically qualified personnel familiar with the project through a process of expert elicitation. This group should consist primarily or solely of current district staff as resources allow. Dependence on non-district participants is not recommended if it replaces participation of those who are familiar with the specific dam. The first term in the equation, I_{Dam}, is the relative importance of the j^{th} dam in the management region under consideration. This importance factor is determined considering various factors, which can include dam age, height, population at risk, economic consequences, etc. This factor is established initially through expert elicitation and then updated only as conditions on the dam change over time. See section 3.1.2 for further information on the dam importance factor. The second term, $I_{DGi,j}$, is a measure of the importance of the particular defense groups in preventing a failure of the dam. This measure is determined through a careful consideration of the various modes of failure and is established through expert elicitation and then updated only as changes occur to the dam over time. For most embankment dams, neither the first nor the second terms in the equation will need to be updated frequently. The final term of the equation is a measure of the condition of each of the defense groups (representing their ability to function satisfactorily in their defense capacity) and can be determined annually based on site inspections.

The process of expert elicitation, as outlined in the main body of this report, is used to estimate the importance of the defense groups for a dam. The rules for assessment of condition based on site inspections are then outlined.

Defense groups were not further subdivided into individual components because the expert panel felt that they could not confidently assess the condition of the individual components of a particular defense group if the components are not accessible for inspection. Additionally, for rating purposes, if the defense

group has lost its ability to function, the expert panel felt that it did not make any difference which of the components failed. For example, the defense group for pressure control in the foundation of an embankment dam constructed over pervious river deposits may consist of an upstream blanket and a series of pressure relief wells. If there is a dangerous buildup of pore pressure, for rating purposes it does not matter which of these components fails, because the result would be the same.

2.3 Overall CI for Dam Prevention System

Priority rankings for the defense groups on a particular dam are a measure of the overall ability of the dam to perform its function of preventing failure. A dam with high priority rankings for multiple defense groups is one that has significant needs. An estimate of the overall condition of the embankment dam, $CI_{Dam\,j}$, can be made by summing the weighted condition indices of the defense groups in accordance with Equation 2.2:

$$CI_{Dam\,j} = \sum_{i=1}^{N_{DG}} I_{DGi,j} \bullet CI_{DGi,j} \qquad \text{(Eq. 2.2)}$$

$CI_{DGi,j}$ = the condition index of the i^{th} defense group on the j^{th} dam

$I_{DGi,j}$ = the importance of the i^{th} defense group on the j^{th} dam

The defense group CI also implicitly includes the evaluator's confidence in the accuracy of the information used in the condition rating. On this basis, the defense group importances and CIs can be used as the sole basis for the CI of the embankment dam. The overall CI for a dam can be monitored over time and thus becomes an indicator of the combined rate of deterioration/ improvement of the prevention system. Note that the overall CI does not include the dam importance factor. Hence, the $CI_{Dam\,j}$ should not be compared between projects for the prioritization of M&R funds.

2.4 Priority Ranking of Monitoring Devices

A parallel methodology for the prioritization of M&R funds on the performance monitoring system is also presented in Chapter 4. The performance monitoring system is defined as the installed instrumentation and visual observational surfaces (e.g., downstream toe area, downstream slope area) used

by the dam expert to obtain specific information in order to assess the condition of the dam. The general form of the priority ranking equation used for the defense groups is also used for ranking monitoring devices ($PR_{MD i,j}$) as follows:

$$PR_{MD i,j} = CF_{Dam\ j} \bullet I_{MD i,j} \bullet \frac{(100 - CI_{MD i,j})}{100} \quad \text{(Eq. 2.3)}$$

$CF_{Dam\ j}$ = the importance of the embankment dam within the USACE inventory (based on consequences of failure)

$I_{MD i,j}$ = the importance of i^{th} monitoring device on the j^{th} embankment dam and ranges from 0 to 1.0 such that the sum of all monitoring importance factors for a particular dam is 1.0

$CI_{MD i,j}$ = the condition index of the i^{th} monitoring device and ranges from 0 to 100 representing the ability of the monitoring device to function.

The set up of the system for a given dam (i.e., the determination of the importance of the embankment dam and determination of the importance of the monitoring devices) must be carried out by technically qualified personnel familiar with the project through a process of expert elicitation. The condition of the monitoring devices is determined during onsite inspections. As is the case with the defense groups, the determination of monitoring device importance is accomplished initially and then updated only as changes in the overall performance of the dam occur (i.e., on an infrequent basis). The dam is to be inspected on a regular basis to determine the condition of the monitoring devices. This can be accomplished as part of ongoing dam safety inspections. The priority ranking expressed in Equation 2.3 will favor the most important monitoring devices on the most important dams that are in the worst condition.

The CI for each monitoring device is a measure of its current state and represents its ability to function satisfactorily as determined during an onsite inspection by technically qualified personnel familiar with the project. The importance factor $I_{Dam\ j}$ is a measure of the relative importance of the dam compared to other dams within the organization. See section 3.1.2 for further information on the dam importance factor. The importance factor $I_{MD i,j}$ is a relative measure of the overall importance of a particular monitoring device in helping to identify a potential failure mode.

The process of expert elicitation, as outlined in the main body of this report, is used to estimate the importance of the embankment dam and of the monitoring devices. The rules for assessment of condition are then outlined to guide an onsite inspection. The basic assumption for the monitoring system is that its current configuration is optimal and the priority rankings are based on this optimal state. Provision has been made for the responsible dam safety engineer to add proposed devices in order to accomplish this "ideal" configuration.

2.5 Overall CI for Dam Monitoring System

The priority rankings for the monitoring devices on a particular dam are a measure of the overall ability of the monitoring system to provide accurate information on failure modes. A monitoring system with high priority rankings for multiple monitoring devices is one that has difficulty in providing accurate information. An estimate of the overall condition of the monitoring system (CI_{MSj}) can be made by summing the weighted condition indices of the monitoring devices in accordance with Equation 2.4:

$$CI_{MS\,j} = \sum_{i=1}^{N_{MD}} I_{MDi,j} \bullet CI_{MDi,j} \qquad \text{(Eq. 2.4)}$$

$CI_{MDi,j}$ = the condition index of the i^{th} monitoring device on the j^{th} dam

$I_{MDi,j}$ = the importance of the i^{th} monitoring device on the j^{th} dam.

The overall CI for a monitoring system can be monitored over time and it becomes an indicator of the combined rate of deterioration/improvement of the monitoring devices. Note that the overall monitoring system CI does not include the dam importance factor. Hence, the $CI_{MS\,j}$ should not be compared between projects for the prioritization of M&R funds. Also note that the overall CI of the monitoring system computed by Equation 2.4 has not been rigorously calibrated against the REMR CI Scale.

3 Methodology for Defense Groups

Priority rankings (PR) for deficiencies in defense groups are performed in accordance with Equation 2.1:

$$PR_{DG\,i,j} = CF_{Dam\,j} \bullet I_{DG\,i,j} \bullet \frac{(100 - CI_{DG\,i,j})}{100}$$

The first term in the equation (Importance of the Embankment Dam) must be determined by principles such as those outlined in section 3.1. The second term in the equation (Importance of the Defense Group) is determined through an expert elicitation process and is related to the relative importance of that group in preventing a failure of the dam. The third term in the equation (Condition of the Defense Group) is determined through an onsite inspection. These terms are explained in detail in the following subsections.

3.1 Importance of Embankment Dam

The risk created by a dam is determined by the potential for failure and the consequences of any type of failure. The embankment dam CI includes partial consideration of factors that determine the potential for failure but no consideration of the consequences. The CI and PRs developed in this report are comprised of sub-system importances determined by relative likelihood of events and sub-system condition ratings. Because the sub-system importance factors are relative within the dam, they do not provide comparibility of risk between dams. As a result, only the sub-system condition ratings create some comparability between dams.

A very limited consideration of the consequences can be made based on hazard potential classification. In Table 3.1, three consequence levels are presented: low, significant, and high. Each level has been assigned a relative score. Since approximately 80% of all Corps dams are high hazard, this factor provides minimal ability to differentiate between dams. An attempt was made to improve the comparibility of priority rankings between dams by slightly refining the assignment of hazard ratings and also considering some of the basic

properties of the dam by making a simplistic quantification of their impact on the performance of the dam. This hazard rating was not implemented, but it is included in Appendix B. It may be useful to some as a tool to assist in prioritization. Its greater benefit is probably as a reminder of important generic parameters in assessing the relative risk created by individual dams. It is expected that further research will result in better procedures for determining the importance of dams, and those procedures may become part of this CI and Corps policy.

Table 3.1. Hazard Potential (assuming failure).

Hazard Potential Classification	Probable Loss of Life	Economic, Environmental, and Lifeline Losses	Consequence Factor (CF)
Low	None expected	Generally limited to the owner only°	0.01
Significant	None expected	Yes, likely to include other in addition to the owner.	0.10
High	Probable – one or more expected		1.00

3.2 Determination of Defense Group Importance

A panel of technically qualified personnel familiar with the project determines the importance of the defense g1roups in a three-step procedure that includes the following:

- establishment of relative likelihood of the various failure modes
- determination of importance of the adverse conditions with respect to each of the failure modes
- determination of importance of the defense groups in preventing the adverse conditions.

Figure 3.1 summarizes this procedure. The three steps are represented as three levels of analysis. Moving between the three levels on Figure 3.1 requires the use of interaction matrices and the posing of three questions. These three steps involve complex interactions between various factors. Such interactions are efficiently managed using a systems approach with interaction matrices.

Table 3.2 summarizes the four failure modes considered here: overtopping, surface erosion, piping, and mass movement. Table 3.3 summarizes the eight

adverse conditions that could lead to the various failure modes. Table 3.4 summarizes the defense groups used to prevent the adverse conditions. The questions necessary to allow the panel to determine defense group importance are elaborated in the following paragraphs.

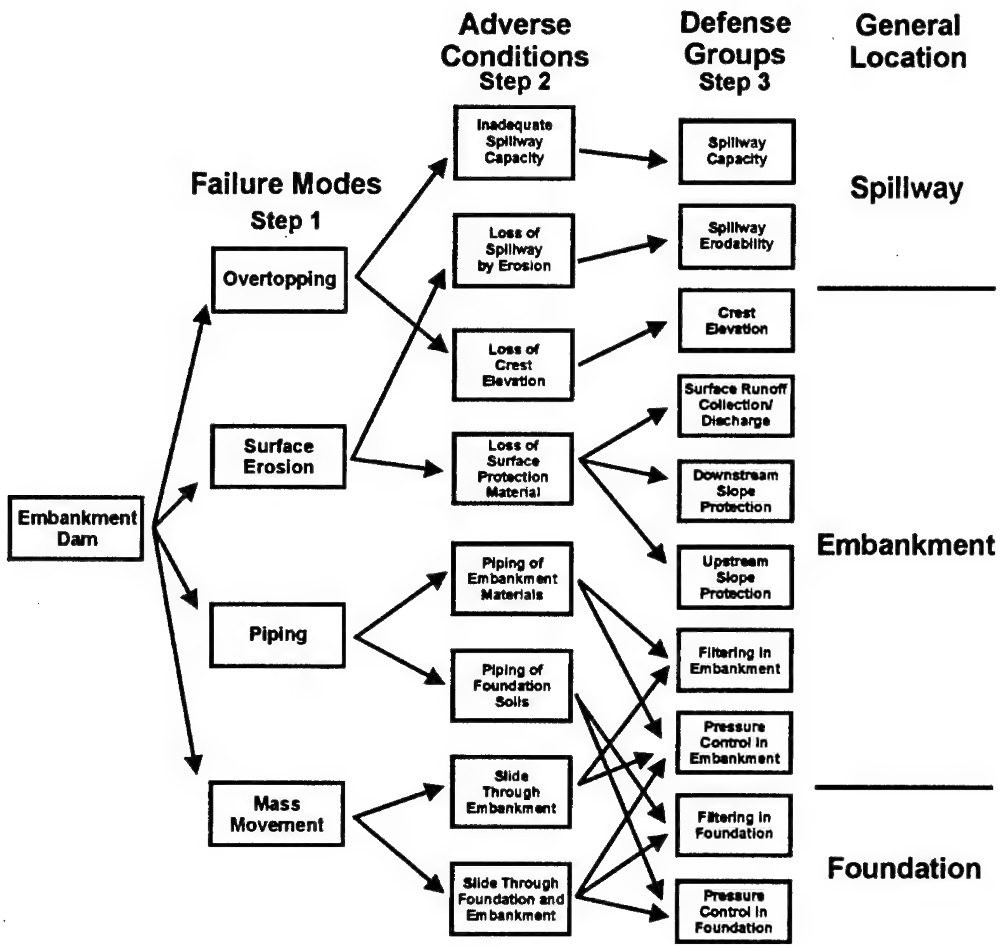

Figure 3.1. Flowchart for defense group importance.

Table 3.2. Failure modes and definitions.

Failure Mode	Definition
Overtopping	Water flowing over the crest of the dam resulting from an uncontrolled rise in the reservoir.
Surface Erosion	Any erosive mechanism that can compromise the integrity of the embankment surfaces or spillway and lead to breach of the dam. This erosion can be caused by wave action, spillway flow, cycles of rain and drought, wind, burrowing animals, human activities, etc.
Piping	The migration of soil particles from locations within the embankment thus creating voids. This internal erosion can be caused by high seepage velocities or inappropriately designed filters.
Mass Movement	Large volumes of embankment and/or foundation material that move along sliding surfaces. This mass movement is generally caused by the buildup of excess pore pressures. Sliding can also be initiated by liquefaction due to earthquake loadings.

Table 3.3. Adverse conditions for embankment dams.

Adverse Condition	Definitions
Inadequate Spillway Capacity	Spillway unable to pass the design flood
Loss of Spillway by Erosion	Erosion of spillway during operation
Loss of Crest Elevation	Crest elevation lowered below design height
Loss of Surface Protection Material	Erosion and loss of surface protection material
Piping of Embankment Materials	Physical removal of embankment core or filter materials under the action of hydraulic gradients
Piping of Foundation Materials	Physical removal of foundation materials under the action of hydraulic gradients
Slide Through the Embankment (Static of Dynamic)	Mass movement of the embankment that involves only the embankment material
Slide Through the Foundation and Embankment (Static or Dynamic)	Mass movement that involves both embankment and foundation materials

Table 3.4. Defense groups for embankment dams.

Defense Group	Purpose
Spillway Capacity	Ability to pass design flow
Spillway Erosion Control	Ability to pass flow without loss of sill
Crest Elevation	Crest elevation relative to design elevation
Surface Runoff Collection Discharge System	Capacity of collection system and ability to remove from dam without erosion
Downstream Slope Protection	Protection from erosion of slope
Upstream Slope Protection	Protection from erosion of slope
Filtering in Embankment	Prevention of the migration of fines
Pressure Control in Embankment	Maintain magnitude of pressures within design parameters
Filtering in Foundation	Prevention of the migration of fines
Pressure Control in Foundation	Maintain magnitude of pressures within design parameters

3.2.1 Relative Likelihood of Failure Modes

In general, the failure modes are not independent; for example, piping or surface erosion can trigger mass movement. However, in assessing the relative likelihood of the failure modes, only the initiating event is considered. Using this approach, the failure modes are considered to be independent. The first step in the procedure is to estimate relative likelihood of failure for each of the failure modes. The relative likelihood of the failure modes, given that failure occurs, are based on dam characteristics such as: (1) site geology, (2) type of dam and appurtenant structures, (3) construction method, (4) historical performance, (5) seismic and hydrologic design considerations, and (6) known defects.

Note that by using *relative* likelihood (assuming the dam has failed), the *actual* probabilities of failure are not expressly considered. The likelihood of failure is not the same for all dams. However, likelihood of failure is related to the condition ratings of the individual defense groups. The CI could be better correlated to actual probabilities by also considering factors such as dam characteristics and design parameters. Some of these factors are considered in a

dam importance factor (refer to Appendix B). A focused discussion involving a panel of dam safety engineers/geologists that has extensive knowledge of the dam is very effective for determining these relative likelihoods. Initially, a presentation is made covering relevant dam characteristics and, after discussion, the panel is requested to answer the following question for each failure mode:

Question One:

Given your understanding of the characteristics of the dam, the foundation conditions, performance history, and potential loads, if you were informed that the dam had failed resulting in an uncontrolled release of the reservoir, what would your opinion be as to the probability that the failure mode being considered was the initiating mode of failure (assuming any component can potentially fail)?

The panel assigns a relative likelihood of failure for each of the modes using the descriptors in Table 3.5. Note that the choices are conditional on the failure of the dam, and they only apply to the relative likelihood of the four failure modes. The choice "very likely" does not mean the dam is likely to fail, only that given failure, that mode is "very likely." Each descriptor has an associated point value. The point values for the four failure modes are then normalized.

Table 3.5. Relative likelihood of failure for failure modes.

Likelihood descriptors	Relative point value
Most likely	5
Very likely	4
Likely	3
Somewhat likely	2
Least likely	1
Not likely	0

3.2.2 Relative Likelihood of Adverse Conditions

The next step is to determine the relative likelihood of the adverse conditions (undesirable events occurring at specific locations on the dam) associated with each of the failure modes. Note that this step is essentially a subdivision of failure modes into more specific (adverse condition) elements. Refer to Figure 3.1. A matrix (subregion of an interaction matrix) is defined with adverse conditions on the rows and failure modes on the columns (Table 3.6).

Importance factors, representing the relative likelihood of the adverse conditions for each failure mode, are placed in the matrix column by column by asking the panel to answer the next question for each adverse condition.

Question Two:

> *Considering the failure mode, what is the relative importance of each adverse condition?*

The relative importance of the adverse conditions can be determined using a relative likelihood scale from 0 to 100 percent. These relative importance factors are placed in the appropriate cells of Table 3.6. The shaded cells represent null entries. For example, the failure mode of overtopping applies only to the adverse conditions of inadequate spillway capacity and loss of crest elevation.

After filling all of the non-null entries, each column is normalized to 1.0 and the entry in each normalized column is multiplied by the importance of the corresponding failure mode, $I[FM_i]$. The relative importance of the adverse conditions $I[AC_j]$ is then obtained as the sum of all terms on the corresponding row. The process of normalizing the column entries, multiplying by the importance of the failure modes, and summing across the rows to get the importance of the adverse conditions, $I[AC_j]$, can be expressed by Equation 3.1:

$$I[AC_j] = \sum_{i=1}^{4} I[AC_j / FM_i] \bullet I[FM_i] \qquad \text{(Eq 3.1)}$$

where:

$I[AC_j \mid FM_i]$ = the normalized importance of the adverse condition j considering the failure mode i (the normalized entries in Table 3.7)

$I[FM_i]$ = the importance of the i^{th} failure mode (Table 3.6).

Table 3.6. Relative importance of the adverse conditions.

	Failure Modes				Importance of Adverse Conditions
	Overtopping	Surface Erosion	Piping	Mass Movement	
Adverse Conditions	$I[FM_1]^*$ (%)	$I[FM_2]^*$ (%)	$I[FM_3]^*$ (%)	$I[FM_4]^*$ (%)	$I[AC_j]$
Inadequate spillway capacity $I[AC_1 \bullet FM]$					
Loss of spillway by erosion $I[AC_2 \bullet FM]$					
Loss of crest elevation $I[AC_3 \bullet FM]$					
Loss of surface protection material $I[AC_4 \bullet FM]$					
Piping of embankment materials $I[AC_5 \bullet FM]$					
Piping of foundation soils $I[AC_6 \bullet FM]$					
Slide through embankment (static or dynamic) $I[AC_7 \bullet FM]$					
Slide through foundation and embankment (static or dynamic) $I[AC_8 \bullet FM]$					
Normalized SUM	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

* Based on Table 3.5.

$$I[AC_j] = \sum_{i=1}^{N_{FM}} I[AC_j \mid FM_i] \bullet I[FM_i]$$

Question Two:

Considering the failure mode, what is the relative importance of each adverse condition?

3.2.3 Importance of Defense Groups

Defense groups on dams may be subdivided into more specific areas of the dam as necessary. A situation will not often occur that would cause consideration of this action. One possibility is if a defense group has two or more distinct problems or combinations of problems in different areas of the dam. By subdividing the defense group, each problem could be evaluated separately.

The relative importance of individual defense groups is determined in a manner similar to that for importance of the adverse conditions. Table 3.7 presents a matrix (subregion of an interaction matrix) with defense groups as rows and adverse conditions as columns. Considering each adverse condition, the panel must answer the following question for each defense group.

Table 3.7. Relative importance of defense groups.

	Adverse Conditions								Importance of Defense Groups
	Inadequate Spillway Capacity	Loss of Spillway By Erosion	Loss of Crest Elevation	Loss of Surface Protection	Piping of Embankment	Piping of Foundation Soils	Slide Through Embankment	Slide Through Foundation and Embankment	
Defense Groups	$I[AC_1]^*$ ( )	$I[AC_2]^*$ ( )	$I[AC_3]^*$ ( )	$I[AC_4]^*$ ( )	$I[AC_5]^*$ ( )	$I[AC_6]^*$ ( )	$I[AC_7]^*$ ( )	$I[AC_8]^*$ ( )	$I[DG_k]$
Spillway Capacity $I[DG{\bullet}AC]$	100								
Spillway Erodability $I[DG{\bullet}AC]$		100							
Crest Elevation $I[DG{\bullet}AC]$			100						
Surface Runoff and Collection/Discharge $I[DG{\bullet}AC]$									
D/S Slope Protection $I[DG{\bullet}AC]$									
U/S Slope Protection $I[DG{\bullet}AC]$									
Filtering in Embankment $I[DG{\bullet}AC]$									
Pressure Control in Embankment $I[DG{\bullet}AC]$									
Filtering in Foundation $I[DG{\bullet}AC]$									
Pressure Control in Foundation $I[DG{\bullet}AC]$									
Normalized SUM	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

* From Table 3.6.

$$I[DG_k] = \sum_{j=1}^{8} I[DG_k \mid AC_j] \bullet I[AC_j]$$

Question Three:

What is the relative importance of each defense group in preventing the adverse condition?

Question Three:

What is the relative importance of each defense group in preventing the adverse condition?

Each non-null entry in Table 3.7 is filled in with a number between 0 and 100 representing the relative importance of the defense groups. Each column entry is normalized by the sum of the column. These normalized scores are then multiplied by the corresponding importance factor for adverse condition and the results are summed across each row. The sum of each row corresponds to the importance of each defense group $I[DG_k]$. The process of normalizing the column entries, multiplying by the corresponding adverse condition importance and summing across the rows to get the importance of each defense group can be expressed by Equation 3.2:

$$I[DG_k] = \sum_{j=1}^{4} I[DG_k / AC_j] \bullet I[AC_j] \qquad \text{(Eq. 3.2)}$$

where:

$I[DG_k \mid AC_j]$ = the normalized importance of defense group k considering adverse condition j

$I[AC_j]$ = the importance of the j^{th} adverse condition.

Note that crest elevation is only relevant to loss of crest elevation, the spillway capacity is only relevant to inadequate spillway capacity, and spillway erodability is only relevant to loss of spillway by erosion. Therefore, the corresponding entries in Table 3.7 are 100. Note also that filtering and pressure control are both related to piping and to mass movement. Removal of fines can open pipes that can destabilize the dam and they can also weaken the soils along a potential failure surface. When answering Question Three for Adverse Conditions 7 and 8 considering filtering, the context is in terms of decreasing the strength of the soils due to removal of fines.

3.3 Determination of Defense Group Condition

The next step in the methodology is to determine the condition of each defense group through inspection. The condition of most of the defense groups cannot be determined directly, but must be inferred from a series of indicators

(evidence of changes). Condition is measured on a generic scale developed by USACE under the REMR program. This scale has been reproduced as Table 2.1. To use the REMR CI Scale, it is necessary to identify ideal and failed conditions for each defense group and to determine ranges in condition for various indicators. The panel has established these ranges and condition definitions.

Tables 3.8 through 3.17 list the indicators and condition definitions for each of the defense groups, and are presented in their respective sections. For each of the indicators, a range in possible CI values is given by Xs for each indicator. The task of the dam inspector is to look for the appropriate indicators related to each of the defense groups and to assign a corresponding condition. Generally, minor instances of the indicator will result in a rating towards the upper end of the range. Severe indicators will rate toward the lower end. The ranges given are only suggested. Where there are multiple occurrences of the same indicator, there is a corresponding tendency for the CI to be in the lower end of the range. The assigned condition must be in agreement with the condition definition and ranges given in the REMR CI Scale (Table 2.1). For the defense group rating, when several indicators are present, the lowest CI from the group is used. In the case where no indicators of distress are present, but there is a known defect, a CI is assigned to the defense group in the suggested range following the REMR CI Scale. Examples of known defects for pressure control in the foundation could be: a leaking diaphragm cutoff wall, an upstream blanket that does not extend far enough upstream, or a toe drain filter that does not meet present filter criteria.

3.3.1 Spillway Capacity Defense Group

Ideal and failed condition definitions for the spillway capacity defense group are based on the spillway's ability to handle design flows. Three indicators can be used to assess the condition of the spillway capacity defense group: (1) a visual assessment of the percent loss of cross-sectional area, (2) whether or not the spillway has sufficient design capacity, and (3) a known defect. An example of a known defect would be a known tendency for instability in the channel slopes. If the spillway is on the Headquarters USACE Dam Safety Assurance priority list for a capacity problem, then it is given a condition of zero. Table 3.8 presents the applicable ranges for these three indicators.

Table 3.8. Condition definition for the spillway capacity defense group.

Spillway Capacity Defense Group							
Ideal Condition	To be able to pass the design flow.						
Failed Condition	Enough blockage so that the dam may be overtopped or the spillway does not meet current criteria.						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
% loss of cross-sectional area							
• 0-10 %						X	X
• 10-25 %				X	X		
• 25-100 %	X	X	X				
Will overtop with observed blockage CI = 0							
Design spillway capacity lower than the current design flood CI = 0[a]							
Known Defects (with no indicator of distress)						X	X

(a) CI = 0 for Corps of Engineers dam on Dam Safety Assurance List for inadequate capacity.

Example of known defects:

- Tendency for instability in the channel slopes.

3.3.2 Spillway Erosion Defense Group

Ideal and failed condition definitions for the spillway erosion defense group are based on the ability of the spillway to pass flow without loss of the sill and/or reservoir. Erodability refers to erosion of spillway material (sill and/or foundation material) during a discharge. In extreme cases, the sill will erode and threaten the integrity of the spillway and/or dam and the project's ability to fulfill its original purpose (retain design pool). Two indicators can be used to assess the condition of the spillway erosion defense group. These indicators are: (1) evidence of erosion (including internal erosion beneath the spillway); and (2) whether or not there is a known defect. An example of a known defect would be the presence of highly erodable material in the spillway. For a Corps of Engineers dam, if the spillway is on the HQ DSA priority list for an erodability deficiency, then it is given a condition of zero. Table 3.9 presents the applicable ranges for these two indicators.

Table 3.9. Condition definition for the spillway erosion defense group.

Spillway Erosion Defense Group							
Ideal Condition	To be able to pass design flow without the loss of the sill.						
Failed Condition	Sill and/or reservoir would be lost due to erosion.						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Erosion [a]							
• none or minor erosion (damage can be repaired with project personnel)					X	X	X
• significant erosion (sill intact but damage extensive enough that repairs must be made by contract)		X	X	X			
• critical erosion (sill lost) [b]	X						
Known defect (with no indicators of distress)					X	X	X

(a) This can include internal erosion of material beneath the spillway.

(b) CI = 0 for Corps of Engineers dam on Dam Safety Assurance List for erodibility.

An example of a known defect is highly erodible material beneath the sill.

3.3.3 Crest Elevation Defense Group

Ideal and failed condition definitions for the crest elevation defense group are based on the design elevations for the crest. There are two indicators that are used to assess condition for the crest elevation. These are: (1) the percentage of the freeboard remaining and (2) whether or not there is a known defect. An example of a known defect would be poor compaction in the core around an instrumentation riser that could lead to excessive settlement of core material. Table 3.10 shows the possible condition ranges for these two indicators.

3.3.4 Surface Runoff Collection/Discharge System

Ideal and failed condition definitions for the surface runoff collection/discharge system are based on the capacity of the collection systems, the types of protective materials, and the existing grades. Four indicators can be used to determine the condition of the surface runoff collection and discharge system: (1) depth of erosion below surface protection, (2) capacity of collection lines, (3) existing surface grades, and (4) known defects (such as erodable materials in collection and discharge ditches or inadequate grade of drains). Table 3.11 shows each of these indicators and allowable ranges for the assignment of condition.

Table 3.10. Condition definition for the crest elevation.

Crest Elevation Defense Group (decrease due to settlement)							
Ideal Condition	Crest at or above design elevation.						
Failed Condition	Crest below surcharge pool.						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Percent of freeboard remaining							
• 75 to 100 %						X	X
• 0 to 75%	X	X	X				
Known defect (no indicators of distress)						X	X

Examples of known defects:

- Poor compaction around an instrumentation riser in the core
- Poor compaction adjacent to a concrete structure.

Table 3.11. Condition definition for the surface runoff collection/discharge system.

Surface Runoff Collection/Discharge System							
Ideal Condition	Capacity of the collection systems, protective materials, and existing grades are sufficient to convey storm drainage away from the dam without erosion.						
Failed Condition	Capacity of the collection systems, protective materials, and existing grades are insufficient to convey storm drainage away from the dam without erosion.						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Depth of erosion below protection							
• 0 to 1 ft						X	X
• 1 to 3 ft			X	X	X		
• greater than 3 ft	X	X	X				
Capacity of collection lines							
• no backup							X
• infrequent backup				X	X	X	
• frequent backup	X	X	X				
Surface grades							
• no ponding							X
• infrequent ponding				X	X	X	
• frequent ponding	X	X	X				
Known defect (no indictors of distress)						X	X

Examples of known defects:

- Erodible materials in trenches and ditches
- Inadequate grade of drains.

3.3.5 Downstream Slope Protection

The defense group for downstream slope protection is applicable to earthen embankment dams with grass cover. The ideal and failed conditions are based on visual evidence of loss of grass cover or the existence of erosion gullies. Three indicators can be used to determine the condition of the downstream slope protection: (1) the presence and depth of ruts and gullies, (2) the observed loss of surface protection material, and (3) known defects such as highly erodable materials. Table 3.12 shows these indicators with corresponding condition ranges.

3.3.6 Upstream Slope Protection

Ideal and failed condition definitions for upstream slope protection are based on observable erosion, deterioration/removal of the slope protection, and exposure of bedding material. Four indicators can be used to assess the condition of the upstream slope protection: (1) observed loss of slope protection material, (2) degradation/breakdown of slope protection material, (3) removal of bedding or protected material, and (4) known defects such as improperly sized stone protection for reservoir fetch and storm conditions. Table 3.13 shows these indicators with corresponding ranges.

Table 3.12. Condition definition for downstream slope protection (applicable to earthen dams with primarily grass cover).

Downstream Slope Protection							
Ideal Condition	No noticeable erosion resulting in changes in design geometry						
Failed Condition	Existence of deep (3 to 4 ft) ruts/gullies and/or 50% loss in surface protection						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Ruts and gullies (erosion into protected soil) [a]							
• 0 to 1 ft deep						X	X
• 1 to 3 ft			X	X	X		
• greater than 3 ft	X	X	X				
Loss of surface protection material							
• 0% to 10 %					X	X	X
• 10% to 25%			X	X	X		
• 25% to 50%		X	X				
• greater than 50%	X						
Known defect (no indicators of distress) [b]						X	X

(a) Use lower end of the scale for multiple occurrences.
(b) Example of known defect:
- erodible downstream material.

Table 3.13. Condition definition for the upstream slope protection.

Upstream Slope Protection							
Ideal Condition	No noticeable erosion or deterioration resulting in changes in design geometry						
Failed Condition	Removal of slope protection resulting in extensive exposure of bedding or protected material						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Loss of slope protection material							
• no noticeable erosion or deterioration							X
• isolated or minor loss or movement of outer layer material				X	X	X	
• significant loss or movement of outer layer material		X	X				
• extensive loss of outer layer material and/or exposure of bedding material	X						
Degradation/breakdown of slope protection							
• isolated/minor					X	X	
• moderate			X	X			
• extensive/major		X					
Removal of bedding or protected material without the loss of outer slope protection							
• isolated/minor					X	X	
• moderate			X	X			
• extensive/major		X					
Known defect (no indicators of distress)						X	X

Example of known defect:

- Improperly sized stone protection for reservoir fetch and storm conditions.

3.3.7 Filtering in Embankment

The ideal and failed conditions for filtering in the embankment are based on prevention of internal erosion (piping) of embankment materials. Three indicators are used to assess the condition of the defense group that filters the flow in the embankment: (1) the existence of turbid flows, (2) the existence of sinkholes or depressions, and (3) the existence of known defects such as segregation of the filter materials or improperly designed filter/drainage system. While recognizing that hydrostatic pressures have an impact upon piping considerations, it is believed that those considerations are adequately treated in "Pressure Control in Embankment" and in the determination of relative importance factors for the defense groups (see Table 3.7). The condition of the filtering group is generally very difficult to determine. Note that, with any known defect in the embankment filtering system, the condition can never be 100 even in the absence of any evidence of the migration of fines. Table 3.14 summarizes these indicators and the corresponding ranges.

Table 3.14. Condition definition for filtering in embankment.

Filtering in Embankment							
Ideal Condition	No migration of fines with a designed filtering system.						
Failed Condition	Persistent migration of fines.						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Turbid flows							
• no evidence							X
• evidence of prior occurrence			X	X	X		
• actively occurring	X	X					
Sinkholes / depressions	X	X	X	X			
Known defects (no indicators of distress)			X	X	X	X	

Examples of known defects:

- Pipeable material without a designed filter system.
- Improperly designed internal filter/drainage system in embankment.

3.3.8 Pressure Control in Embankment

The ideal and failed conditions for the pressure control group in the embankment are based upon projected magnitudes of pore pressures in relationship to design values and calculated factors of safety against slope instability. Seven indicators are used to assess the condition of the pressure control group in the embankment: (1) piezometric levels at or below design levels, (2) piezometric levels above design levels, (3) uncontrolled seepage, (4) changes in controlled seepage, (5) differential movement in the embankment, (6) computed factors of safety from slope stability analyses compared to required minimum factors of safety, and (7) known defects (such as improperly designed drains). Although indicators (3) and (4) might suggest a developing piping problem, they are considered within the pressure control system. Table 3.15 presents these indicators and the corresponding ranges that can be used by inspectors to assign condition.

3.3.9 Filtering in Foundation

The ideal and failed conditions for filtering in the foundation are the same as those for "Filtering in Embankment" and are based on the prevention of internal erosion (piping) of foundation materials. Three indicators are used to assess the condition of the defense group that filters flow in the foundation: (1) the existence of turbid flows, (2) the existence of sinkholes or surface depressions, and (3) the presence of known defects such as segregation of filter materials or

Table 3.15. Condition definition for pressure control in embankment.

Pressure Control in Embankment							
Ideal Condition	Magnitude of pressures within design parameters projected at design pool.						
Failed Condition	Pressures sufficient to result in FS < 1 at design pool for mass movement.						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Piezometric levels at or below design levels [a]							
• constant						X	X
• increasing				X	X	X	X
Piezometric levels above design level [a]							
• constant		X	X	X	X		
• increasing	X	X	X				
Uncontrolled seepage							
• changes in surface vegetation					X	X	X
• soft/wet areas				X	X	X	
• constant flow			X	X	X		
• increasing flow	X	X	X				
Change in controlled seepage		X	X	X	X	X	
Differential movement (e.g., cracking, shallow slides, bulging, between fixed and floating structures)							
• minor / localized			X	X	X	X	
• major / extensive	X	X	X				
F.S. mass movement							
• F.S.≥ Design F.S. [b]							X
• 1.0 < F.S. ≤ Design F.S. [b]		X	X	X	X	X	
• F.S. < 1.0	X						
Known defect (no indicators of distress)						X	X

(a) Projected in relationship to design pools.
(b) Required design minimum factor of safety.

Example of known defect:
- Improperly designed drains.

improperly designed filter/drainage system. While recognizing that hydrostatic pressures have an impact upon piping, it is believed that those considerations are adequately treated in "Pressure Control in Foundation" and through the relative importance determinations for the defense groups (refer to Table 3.7). Table 3.16 summarizes these indicators and the corresponding ranges that can be assigned by the onsite inspector. The condition of the filtering group is generally very difficult to determine. Note that if pipeable material is present without a designed filtering system, the condition can never be 100, even in the absence of any evidence of the migration of fines.

Table 3.16. Condition definition for filtering in foundation.

Filtering in Foundation							
Ideal Condition	No migration of fines with a designed filtering system.						
Failed Condition	Persistent migration of fines.						
Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Turbid flows							
• no evidence							X
• evidence of prior occurrence			X	X	X		
• actively occurring	X	X					
Sinkholes / depressions	X	X	X	X			
Known defect (no indicators of distress)			X	X	X	X	

Examples of known defects:

- Segregation of the filter materials
- Improperly designed internal filter/drainage system in foundation.

3.3.10 Pressure Control in Foundation

The ideal and failed conditions for the pressure control group in the foundation are the same as those for "Pressure Control in Embankment" and are based on projected magnitudes of pore pressures in relationship to design values and calculated factors of safety against slope instability. Seven indicators are used to assess the condition of the pressure control group in the foundation: (1) projected piezometric levels at or below design levels, (2) projected piezometric levels above design levels, (3) uncontrolled seepage, (4) changes in controlled seepage, (5) differential movement in the embankment, (6) computed factors of safety from slope stability analyses compared to required minimum factors of safety, and (7) known defects such as an improperly designed pressure relief system, a defective cutoff wall, inadequate upstream impervious blanket, etc. Although indicators (3) and (4) might suggest a developing piping problem, they are considered within the pressure control system. Table 3.17 presents these indicators and the corresponding ranges that can be used by inspectors to assign condition.

Table 3.17. Condition definition for pressure control in foundation.

Pressure Control in Foundation	
Ideal Condition	Magnitude of pressures within design parameters projected at design pool.
Failed Condition	Pressures sufficient to result in FS < 1 at design pool for mass movement.

Indicators	**0-9**	**10-24**	**25-39**	**40-54**	**55-69**	**70-84**	**85-100**
Piezometric levels at or below design level [(a)]							
• Constant						X	X
• Increasing				X	X	X	X
Piezometric levels above design level [(a)]							
• Constant		X	X	X	X		
• Increasing	X	X	X				
Uncontrolled seepage							
• changes in surface vegetation					X	X	X
• soft/wet areas				X	X	X	
• constant flow			X	X	X		
• increasing flow	X	X	X				
Change in controlled seepage		X	X	X	X	X	
Differential movement (e.g., cracking, shallow slides, bulging)							
• minor / localized			X	X	X	X	
• major / extensive	X	X	X				
F.S. mass movement							
• F.S.≥ Design F.S. [(b)]							X
• 1.0 < F.S. ≤ Design F.S. [(b)]		X	X	X	X	X	
• F.S. < 1.0	X						
Known defect (no indicators of distress)						X	X

(a) Projected in relationship to design pools.
(b) Required design minimum factor of safety (static or dynamic).

Examples of known defects:
- improperly designed pressure relief system
- inadequate cutoff
- inadequate upstream impervious blanket
- reduced capacity of relief wells

3.4 Calculation of Priority Ranking for Defense Groups

The priority rankings for the defense groups are obtained from Equation 2.1.

$$PR_{DG\,i,j} = I_{Dam\,j} \bullet I_{DG\,i,j} \bullet \frac{(100 - CI_{DG\,i,j})}{100}$$

Table 3.18 is a summary of the calculation procedure. The summation of the importance factors for the defense groups must be equal to 1.0. Among any group of rated dams, the defense group on the most important dam with the worst condition will have the highest priority ranking.

Table 3.18. Priority ranking calculation of defense groups.

	Importance		CI	Ranking
Defense Groups	I_{Dam}	I_{DG}	CI_{DG}	PR_{DG} (a)
Spillway Capacity [DG_1]				
Spillway Erodability [DG_2]				
Crest elevation [DG_3]				
Surface runoff collection/discharge system [DG_4]				
D/S slope protection [DG_5]				
U/S slope protection [DG_6]				
Filtering in embankment [DG_7]				
Pressure control in embankment [DG_8]				
Filtering in foundation [DG_9]				
Pressure control in foundation [DG_{10}]				
SUM		1.0		
Overall Condition Index [CI_{Dam}] (b) Defense Groups				

(a) From Equation (2.1)

$$PR_{DGi} = I_{Dam} \cdot I_{DGi} \cdot \frac{(100 - CI_{DGi})}{(100)}$$

(b) Equation (2.2)

$$CI_{Dam\,j} = \sum_{i=1}^{N_{DG}} I_{DGi,j} \bullet CI_{DGi,j}$$

3.5 Calculation of Overall CI for the Dam Prevention System

The overall CI for the dam prevention system can be calculated by summing the weighted CIs for the defense groups in accordance with Equation 2.2.

$$CI_{Dam\,j} = \sum_{i=1}^{N_{DG}} I_{DGi,j} \bullet CI_{DGi,j}$$

The overall CI for a dam can be monitored over time and thus can become an indicator of the rate of deterioration/improvement of the prevention system for the dam. Note that relativity of the overall CI of one dam versus another can only be achieved with the inclusion of the dam importance factor. Hence, the $CI_{Dam\,j}$ should not be compared between projects for the prioritization of M&R funds.

4 Methodology for Monitoring Devices

Priority rankings for deficiencies of monitoring devices are performed in accordance with Equation 2.3.

$$PR_{MDi,j} = I_{Dam\,j} \bullet I_{MDi,j} \bullet \frac{(100 - CI_{MDi,j})}{100}$$

The first term in the equation (Importance of the Embankment Dam) must be determined by principles such as those outlined in section 3.1. The second term in the equation (Importance of the Monitoring Device) is determined through an expert elicitation process and is related to the relative importance of that device in detecting the presence or absence of adverse conditions on the dam. The third term in the equation (Condition of the Monitoring Device) is determined through an onsite inspection. These terms are explained in detail in the following subsections.

4.1 Importance of Embankment Dam

The importance of the embankment dam for the monitoring devices is the same as that outlined in section 3.1 for the prevention system.

4.2 Determination of Monitoring Device Importance

The monitoring system comprises all the devices (instrumentation and observation surfaces) that are used by dam safety engineers to assess the performance of the various components of the dam. Although the monitoring system is a valuable tool that can be used for monitoring performance and safety, it is not a standalone solution to the continuing evaluation of embankment performance. The determination of the need for instrumentation must always be kept in perspective. In the words of Dr. Ralph Peck, quoted by Dunnicliff (1988):

> Every instrument on a project should be selected and placed to assist with answering a specific question; if there is no question, there should be no instrumentation. Instrumentation cannot guarantee good design, trouble free construction, or long-term maintenance-free operation. The

wrong type of instruments placed in inappropriate locations can provide information that can be confusing, or divert attention away from other signs of potential distress. Instrumentation cannot indicate signs of impending deterioration or failure unless they happen to be at the right location. Data from monitoring devices are not intended to be the sole basis for embankment evaluation; they are intended to provide data that will help the dam safety engineers assess the actual condition and predict future performance.

Monitoring devices can be divided into two groups: (1) those that provide quantitative data (i.e., instruments such as piezometers, flow meters, weirs, etc.), and (2) those that provide qualitative data such as visual observation surfaces (i.e., upstream slope, spillway training wall, etc.). These devices have widely varying diagnostic values depending on their ability to correctly assess the presence or absence of undesirable conditions that could lead to failure of the embankment dam. Any one monitoring device can provide information that may be indicative of multiple adverse conditions and its information must be considered with all other available information to make a rational decision about dam condition. Frequent dam inspections and continuing analyses of monitoring data provide the dam safety engineer with the means to better evaluate embankment dam performance.

The information processed during a dam inspection and data analyses can be modeled by the flow chart depicted in Figure 4.1. Monitoring devices provide information on indicators of adverse conditions, which in turn are used to deduce the presence or absence of adverse conditions that could lead to failure by one or more modes.

The relative importance of monitoring devices is determined by a panel of technically qualified personnel familiar with the project in a four-step procedure that includes the following:

- the establishment of relative likelihood of the various failure modes

- the determination of importance of the adverse conditions with respect to each of the failure modes

- the determination of importance of indicators in signaling the presence or absence of the adverse conditions

* the determination of importance of the monitoring devices in evaluating the various indicators.

Figure 4.2 summarizes this procedure. The four steps are represented as four levels of analysis. Moving between the four levels on Figure 4.2 requires the use of interaction matrices and the posing of four questions. These four steps involve complex interactions between various factors. Such interactions are efficiently managed using a systems approach with interaction matrices.

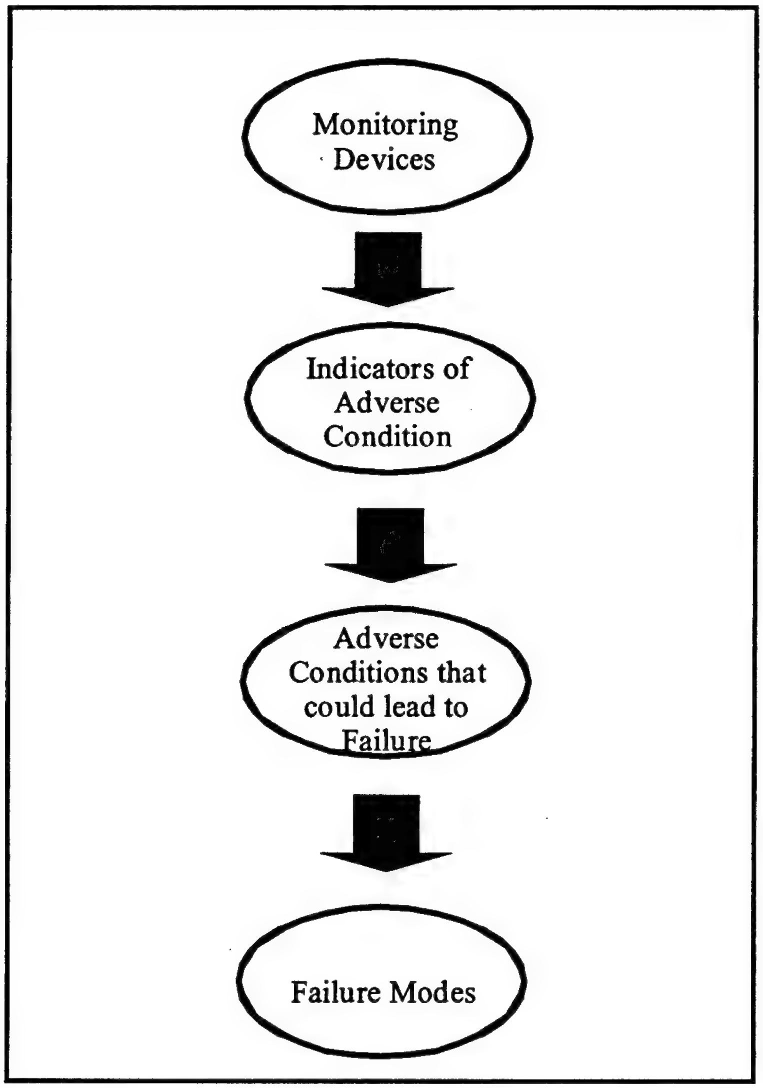

Figure 4.1. Flowchart for information during performance monitoring.

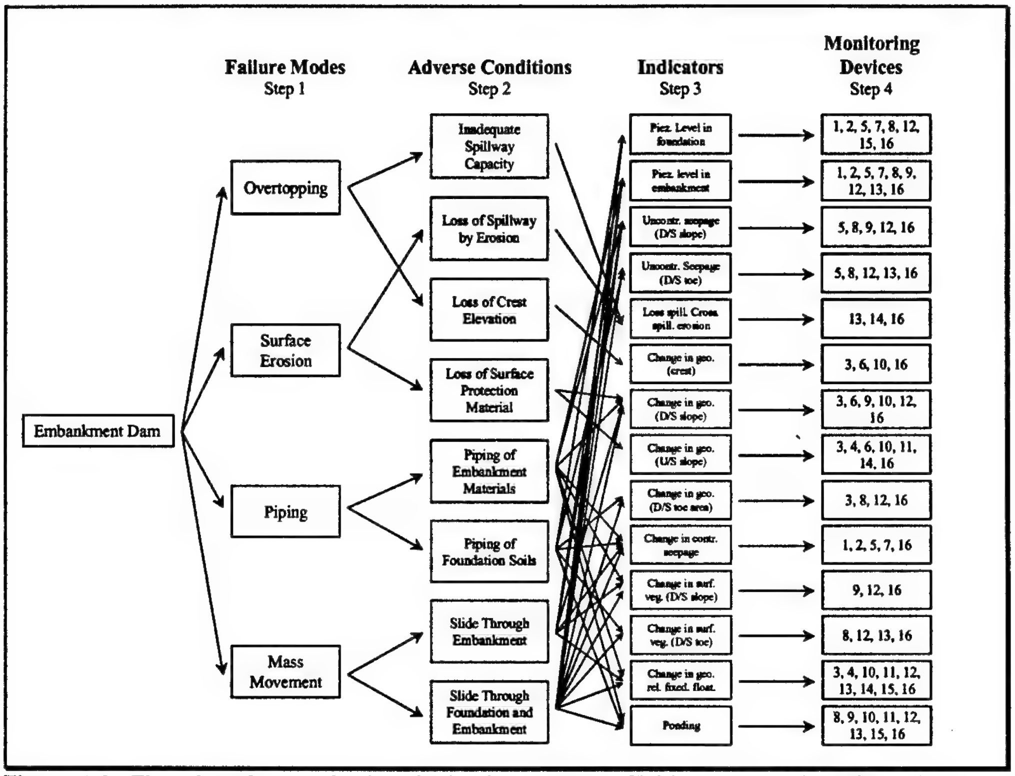

Figure 4.2. Flowchart for monitoring device importance. Table 4.3 (p 43) identifies the monitoring devices listed under Step 4.

4.2.1 Relative Likelihood of Failure Modes

Use the results from section 3.2.1 as the importance factors for the failure modes (relative likelihood of failure).

4.2.2 Relative Likelihood of Adverse Conditions

Use the results from section 3.2.2 as the importance factors for the adverse conditions. The same adverse conditions used for the prevention system are considered herein.

4.2.3 Importance of Indicators

Indicators are physical signs used to deduce the presence or absence of impending adverse conditions. Table 4.1 presents a list of these indicators and some brief explanations for each. Note that these indicators are a subset of those used to assess condition of the defense groups in Tables 3.8 through 3.17 and are related to information that can be collected during an onsite inspection. The importance of the indicators is determined by considering their relative value

with respect to the adverse conditions. Their value is defined qualitatively as the relative likelihood of making a correct assessment about the presence or absence of a particular adverse condition. Some of the indicators will not be relevant to some of the adverse conditions and, hence, will have no value for those particular adverse conditions. Note also that the value of indicators for one adverse condition does not depend on the value of the indicators for another adverse condition. Table 4.2 presents the 14 indicators and the 8 adverse conditions in a matrix (subregion of an interaction matrix) to assist in the determination of relative value. The indicators are placed in the rows and the adverse conditions in the columns. Considering each adverse condition in turn, the panel answers the following question.

Question One:

Considering each adverse condition, what is the relative value of that indicator for monitoring?

In this context, the relative value refers to the value of the indicator in deducing the presence or absence of impending adverse conditions. The panel places a numerical score with a range of 0 to 100 in each of the corresponding matrix locations. The shaded cells in the matrix correspond to null entries (indicators that have no diagnostic value for a particular adverse condition).

After completing the codification of the entire matrix (considering all adverse conditions), the individual scores are normalized by the corresponding total column score. These normalized scores are then multiplied by the corresponding column importance (relative importance of the corresponding adverse condition) and the rows are summed to give the overall importance factors for the indicators, $I[Ind_k]$. These mathematical operations can be summarized by Equation 4.1.

$$I[Ind_k] = \sum_{j=1}^{N_{AC}} I[Ind_k / AC_j] \bullet I[AC_j] \qquad \text{(Eq. 4.1)}$$

$I[Ind_k | AC_j]$ = the normalized column score from Table 4.2 (normalized relative importance considering adverse condition j)

$I[AC_j]$ = the importance of adverse condition j (determined as per section 3.1.2).

Note that the only indicator for "Inadequate Spillway Capacity" and "Loss of Spillway by Erosion" is "Spillway cross-section and erosion of spillway," which means the corresponding entries in Table 4.2 are 100.

Table 4.1. Indicators of adverse conditions.

Indicator	Comments
Piezometric levels in foundation	Referring either to the magnitude or as inferred from a flow net to calculate gradients
Piezometric levels in embankment	Referring either to the magnitude or as inferred from a flow net to calculate gradients
Uncontrolled seepage (turbid or clear) at downstream slope area	Unplanned and unfiltered surface seepage at the D/S slope area (turbid refers to removal of soil)
Uncontrolled seepage (turbid or clear) at the downstream toe area	Unplanned and unfiltered surface seepage at the D/S slope area (turbid refers to removal of soil)
Change in controlled seepage (if turbid then considered to be uncontrolled)	Seepage quantities measured at control locations (e.g., toe drains, pressure relief wells)
Changes in surface vegetation (D/S slope)	Visible changes in the amount or coloration of vegetation on the embankment dam or adjacent regions in the general vicinity of the D/S slope
Changes in surface vegetation (D/S toe area)	Visible changes in the amount or coloration of vegetation on the embankment dam or adjacent regions in the general vicinity of the D/S slope
Loss of spillway cross-section and erosion of spillway	Obstruction of spillway by debris, accumulation of rock, existence of trees, etc. or erosion of spillway threatening the integrity of the sill
Changes in geometry (crest)	Visible or measurable differences between design geometry and current conditions
Changes in geometry (D/S slope)	Visible or measurable differences between design geometry and current conditions
Changes in geometry (U/S slope)	Visible or measurable differences between design geometry and current conditions
Changes in geometry (D/S toe area)	Visible or measurable differences between design geometry and current conditions
Changes in geometry (relative movement between fixed and floating components)	Visible or measured evidence of relative displacements between objects resting on the embankment dam and those resting on the foundation
Ponding	Standing water in inappropriate areas

Table 4.2. Relative importance of indicators.

	Adverse Conditions								
	Inadequate Spillway Capacity	Loss of Spillway by Erosion	Loss of Crest Elevation	Loss of Surface Protection	Piping of Embankment	Piping of Foundation Soils	Slide Through Embankment	Slide Through Foundation and Emb.	Importance of Indicators
Indicators	$I[AC_1]$	$I[AC_2]$	$I[AC_3]$	$I[AC_4]$	$I[AC_5]$	$I[AC_6]$	$I[AC_7]$	$I[AC_8]$	$I[Ind_k]$
(1) PL in foundation $[Ind_1 \cdot AC]$									
(2) PL in embankment $[Ind_2 \cdot AC]$									
(3) Uncontrolled seepage (D/S slope area) $[Ind_3 \cdot AC]$									
(4) Uncontrolled seepage (D/S toe) $[Ind_4 \cdot AC]$									
(5) Spillway cross-section $[Ind_5 \cdot AC]$	100	100							
(6) Change in geometry (crest) $[Ind_6 \cdot AC]$									
(7) Change in geometry (D/S slope) $[Ind_7 \cdot AC]$									
(8) Change in geometry (U/S slope) $[Ind_8 \cdot AC]$									
(9) Change in geometry (D/S toe area) $[Ind_9 \cdot AC]$									
(10) Change in controlled seepage $[Ind_{10} \cdot AC]$									
(11) Change in surface vegetation (D/S slope) $[Ind_{11} \cdot AC]$									
(12) Change in surface vegetation (D/S toe area) $[Ind_{12} \cdot AC]$									
(13) Change in geometry (relative movement fixed and floating components) $[Ind_{13} \cdot AC]$									
(14) Ponding $[Ind_{14} \cdot AC]$									
Normalized SUM	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

$$I[Ind_k] = \sum_{j=1}^{N_{AC}} I[Ind_k \mid AC_j] \bullet I[AC_j]$$

Question One:

Considering each adverse condition, what is the relative importance of that indicator for monitoring?

4.2.4 Importance of Monitoring Devices

Monitoring devices include both instrumentation and visual observation surfaces. They provide direct information on the presence or absence of indicators of adverse conditions. Table 4.3 lists monitoring devices. Monitoring devices in the same strategic location on the dam can be grouped if it is assumed that they will have the same importance. For example, if a specific dam has five

piezometers located in the foundation and six in the embankment, and if the relative importance of the five piezometers in the embankment are considered to be the same, then they can be grouped and labeled as monitoring devices in the embankment. The same applies to the piezometers in the foundation.

The grouping of monitoring devices is subject to four rules: (1) they must provide the same type of information (i.e., porewater pressure from piezometers), (2) they must have the same relative importance (i.e., same diagnostic value), (3) they must be monitoring a common feature (regardless of their condition), and (4) they must not be grouped according to condition.

When M&R activities involve the installation of new monitoring devices, the dam safety engineer must add the proposed monitoring devices (new) to the list of existing devices. The relative importance of the new monitoring device is obtained by considering that the device is already present on the dam. The priority ranking for the new monitoring device is obtained by setting the CI equal to zero (given that the device is not yet providing any information). Monitoring devices not specifically listed in Table 4.3 but proposed as new devices must be clearly defined before being added to the list and must follow the four rules explained earlier.

Table 4.3. Individual monitoring devices or groups of monitoring devices.

Individual or Groups of Monitoring Devices
(1) Piezometers or groups of piezometers at strategic locations
(2) Flow observations at relief wells (or groupings of relief wells)
(3) Surface monuments (or groupings of surface monuments)
(4) Settlement pins on bridges or other structures
(5) Flow observation at toe drain
(6) Slope inclinometers (or groupings of slope inclinometers)
(7) Weirs (or groupings of weirs)
(8) Downstream toe area
(9) Downstream slope area
(10) Crest and shoulders
(11) Upstream slope
(12) Surface at boundary between dissimilar materials (outflow works)
(13) Surface at boundary between dissimilar materials (Surfaces within and near spillway)
(14) Spillway training wall
(15) Abutment surfaces
(16) Proposed devices (or groupings of proposed devices)

It is common for dams to have monitoring deficiencies that, in the judgement of dam safety personnel, do not merit the addition of new devices to correct the deficiency. One example would be a tailwater that hinders the ability to monitor seepage, piping, and other indicators at the toe of the dam. While an additional device (e.g., periodic inspection by divers) could be proposed, in many cases additional monitoring such as this is not realistically considered. When new monitoring devices are not included in the rating as proposed devices for poorly monitored indicators, the CI evaluation results can be misleading. The existence of indicators, particularly important ones, with ineffective monitoring devices will result in inflated importances for those monitoring devices. There will be indicators with inadequate monitoring that will not be reflected in the priority rankings or the CI for detection.

Table 4.4 presents a matrix (subregion of an interaction matrix) for determining the relative importance of the monitoring devices by considering their value for each of the indicators of adverse condition. The monitoring devices are placed in the rows, and the indicators are placed in the columns. The matrix is coded column by column (one indicator at a time) by a panel answering the following question:

Question Two:

> *Considering each indicator, what is the relative value of each monitoring device?*

In this context, the relative value refers to the ability of the monitoring device to provide direct information on the presence or absence of the indicators. A numerical score is given for each relevant monitoring device using a scale from 0 to 100. It is useful to rule out the monitoring devices that are not relevant to a particular adverse condition prior to coding the remaining entries. After completing the matrix for all indicators, each of the column scores are normalized by the column sum and multiplied by the corresponding indicator importance (from Table 4.2) and each row is summed. The resulting scores will be the importance of the monitoring devices, $I[MD_l]$. This process of normalizing by the column score, multiplying by the indicator importance, and summing across the rows can be expressed by Equation 4.2.

$$I[MD_l](1) = \sum_{k=1}^{N_{Ind}} I[MD_l \mid Ind_k] \bullet I[Ind_k] \qquad \text{(Eq 4.2)}$$

Table 4.4. Relative importance of monitoring devices.

	Indicators of Adverse Condition														$I[MD]$
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Monitoring Devices	$I[Ind_1]$	$I[Ind_2]$	$I[Ind_3]$	$I[Ind_4]$	$I[Ind_5]$	$I[Ind_6]$	$I[Ind_7]$	$I[Ind_8]$	$I[Ind_9]$	$I[Ind_{10}]$	$I[Ind_{11}]$	$I[Ind_{12}]$	$I[Ind_{13}]$	$I[Ind_{14}]$	
(1) Piezometers (location)															
(2) Flow Observations at relief wells															
(3) Surface Monuments															
(4) Settlement pins															
(5) Flow observation at toe drain															
(6) Slope inclinometers (location)															
(7) Weirs															
(8) Downstream toe area															
(9) Downstream slope area															
(10) Crest and shoulders															
(11) Upstream slope															
(12) Surface boundaries (outflow works)															
(13) Surface boundaries (spillway)															
(14) Spillway training wall															
(15) Abutment surfaces															
(16) Proposed devices															
Normalized Sum	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

$$I[MD_l] = \sum_{k=1}^{N_{Ind}} I[MD_l \mid Ind_k] \bullet I[Ind_k]$$

Question Two: *Considering each indicator, what is the relative value of each monitoring device?*

$I[MD_l \mid Ind_k]$ = the relative diagnostic value of monitoring device l considering indicator k

$I[Ind_k]$ = the importance of indicator k.

Note: If MD_l is a group of devices, $I[MD_l]$ will be equally divided between the individual devices.

4.3 Determination of Monitoring Device Condition

The CIs for monitoring devices are summarized in Table 4.5. The basis for the condition definition of the monitoring devices is their ability to provide valuable information. Table 4.5 is used by inspectors to determine the condition of each monitoring device during a site inspection. These condition definitions were established by the expert panel and quantify the level of performance of each monitoring device. Ideal (CI=100) and failed (CI=0) conditions are defined. For example, a piezometer that is providing accurate data is given a CI=100 and one that is not providing accurate data is given a CI=0. Note that, for groups of devices (e.g., 10 piezometers), the CI should be calculated as a weighted average of the CI's for the group. If one piezometer out of ten is not functioning, the CI for the group would be $(9(100) + 1(0)) / (10) = 90$.

Monitoring devices can be divided into two groups: (1) those that provide quantitative data (i.e., instruments such as piezometers, flow observations at relief wells, weirs, etc.), and (2) those that provide qualitative data such as observation surfaces (i.e., upstream slope, spillway training wall, etc.). For quantitative data, ideal and failed conditions are defined with respect to the availability and quality of the collected data. Not only is the schedule for reading instruments determined by the inspection team, but they are also responsible for deciding which, if any, of the data requires recording. An intermediate state exists if information is being collected at less than the prescribed rate. For observation surfaces, the definitions of ideal and failed conditions are based on accessibility (can inspect the whole area) of the monitoring device. It was deemed imperative by the development experts that most observation surfaces be fully inspectable. This accessibility was necessary, in part, because it was deemed to be a required business practice regardless of the condition for monitoring. The one observation surface with an intermediate state for inspection access is the downstream toe. This should not be interpreted to mean that

the toe is any less important. The reason for an intermediate state was the effect of variation in determinations by Districts of how far downstream the toe extends. A visual observation surface inspected at less than the prescribed intervals should be given a 40.

Table 4.5. Condition index definition for monitoring devices.

Monitoring Device	CI	Description
Piezometer	100 40 0	Providing data, no evidence of malfunction Providing data at less than prescribed intervals[a] Not providing accurate data, not functioning
Flow observations at relief wells	100 40 0	Providing data Providing data at less than prescribed intervals[a] Not able to inspect, not providing accurate data
Surface monuments (markers)	100 40 0	Providing data Providing data at less than prescribed intervals[a] Not providing accurate data, evidence of disturbance
Settlement pins on bridges or other structures	100 40 0	Providing data Providing data at less than prescribed intervals[a] Not providing accurate data, evidence of disturbance
Flow observation at toe drain	100 40 0	Providing data Providing data at less than prescribed intervals[a] Not able to inspect, not providing accurate data
Slope inclinometer	100 40 0	Providing data, no evidence of malfunction Providing data at less than prescribed intervals[a] Not providing accurate data, not functioning
Weirs	100 40 0	Providing data, no evidence of malfunction Providing data at less than prescribed intervals[a] Not providing accurate data, not functioning
Downstream toe area	100 40 0	Can inspect the area[b] Area partially obstructed from inspection or inspected at less than prescribed interval[a] Cannot inspect the area
Downstream slope area	100 40 0	Can inspect the area[b] Area inspected at less than prescribed interval[a] Cannot inspect the area
Crest and shoulders	100 40 0	Can inspect the area[b] Area inspected at less than prescribed interval[a] Cannot inspect the area
Upstream slope	100 40 0	Can inspect the area[b] Area inspected at less than prescribed interval[a] Cannot inspect the area
Surface at boundary between dissimilar materials (outflow)	100 40 0	Can inspect the area[b] Area inspected at less than prescribed interval[a] Cannot inspect the area
Surface at boundary between dissimilar materials (Surfaces within and near Spillway)	100 40 0	Can inspect the area[b] Area inspected at less than prescribed interval[a] Cannot inspect the area
Spillway training wall	100 40 0	Can inspect the area[b] Area inspected at less than prescribed interval[a] Cannot inspect the area
Abutment surfaces	100 40 0	Can inspect the area[b] Area inspected at less than prescribed interval[a] Cannot inspect the area

(a) The prescribed intervals are to be determined by the dam's inspection team.
(b) The area is dam specific and defined by the inspection team.

4.4 Calculation of Priority Ranking for Monitoring Devices

Table 4.6 can be used to evaluate Equation 2.3. Note that the summation of importance factors for the individual monitoring devices must be equal to 1.0. In a particular organization, the most important monitoring device on the most important dam in the worst condition will have the highest overall priority ranking.

Table 4.6. Priority ranking calculation of monitoring devices.

Monitoring Devices	Importance		CI	Ranking
	I_{Dam}	I_{MD}	CI_{MD}	PR_{MD} (a)
Piezometer				
Flow observations at relief wells				
Flow observation at toe drain				
Weirs				
Slope inclinometer				
Downstream toe area				
Downstream slope area				
Crest and shoulders				
Upstream slope				
Abutment surfaces				
Surface monuments (markers)				
Settlement pins on bridges or other structures				
Surface at boundary between dissimilar materials (outflow)				
Surface at boundary between dissimilar materials (Surfaces within and near Spillway)				
Spillway training wall				
Proposed devices				
SUM		1.0		
Monitoring CI (b)				

(a) From Equation 2.3

$$PR_{MDi} = I_{Dam} \cdot I_{MDi} \cdot \frac{(100 - CI_{MDi})}{100}$$

(b) From Equation 2.4

$$CI_{MS} = \sum_{i=1}^{N_{MD}} I_{MDi} \cdot CI_{MDi}$$

4.5 Calculation of Overall CI for the Dam Monitoring System

The overall CI for the dam monitoring system can be calculated by summing the weighted CIs for the monitoring devices in accordance with Equation 2.4:

$$CI_{MS\,j} = \sum_{i=1}^{N_{MD}} I_{MDi,j} \bullet CI_{MDi,j}$$

The overall CI for a dam monitoring system can be tracked over time and becomes an indicator of the system's rate of deterioration/improvement. Note that relativity of the overall CI of one dam versus another can only be achieved with the inclusion of the dam importance factor. Hence, $CI_{MS\,j}$ should not be compared between projects for the prioritization of M&R funds. Also note that the overall CI of the monitoring system computed by Equation 2.4 has not been rigorously calibrated against the REMR CI Scale.

5 Conclusions and Recommendations

5.1 Conclusions

The existing decision process for management of existing facilities consists of many interim decisions. Often these decisions are made implicitly and are not evaluated separately. The procedures for embankment dams described in this report form a methodology for explicitly addressing many of these decisions. These procedures were developed with the intent of creating a simple process to address the most important issues related to the performance of an embankment dam and to significantly reduce the complexity by eliminating issues that would not impact the final result. The process can be used to evaluate, quantify, and communicate geotechnically related M&R priorities for embankment dams. Software has been developed to record the information and compute the results.

The results obtained by using this methodology will reflect the judgments of the panel of engineers and geologists who implement it. This panel should reach a consensus for all questions. The methodology permits the rapid identification of incorrectly answered questions and assists in the resolution of differences in the case where a consensus is not immediately achieved. It is expected that the CI ratings for the defense groups and monitoring devices could easily be updated annually corresponding to existing annual inspections. The collection and recording of this information can be done very quickly. On the other hand, the process of entering the importances into the matrices to calculate the importance factors is more demanding and time consuming. Fortunately, it is only necessary to enter the importances when significant changes in the performance of the dam result in changes in the importance factors. For most dams, changes will occur infrequently or not at all over the life of the dam, but the importances should be verified on a regular schedule (i.e., corresponding to periodic inspections).

The safety of a dam depends on a complex interaction of many parameters, some of which are not considered in the embankment dam CI. It is not and should not be used as a dam safety index. The CI, particularly the process to

determine the CI, may enhance the evaluation of dam safety information. The CI indicates that the dam with the lower CI may be the better dam on which to spend M&R money. This rating does not imply that the probability of failure is higher for the lower rated dam. The overall CI is a measure of the need for M&R but not of its priority. Therefore, it should not be used to prioritize M&R activities. Priority rankings are intended to assist in ranking M&R activities for a dam. Priority rankings should not be used as the sole basis for prioritization. They do not include adequate consideration of the consequences of unsatisfactory performance nor do they consider other factors such as repair cost, repair effectiveness, efficiencies gained by grouping repairs, repair cost changes due to delay, etc.

Rating procedures for embankment dams presented in this report have had sufficient development and testing to warrant distribution on a wider basis. However, it should still be considered to be in a developmental stage.

5.2 Recommendations

A very limited consideration of the consequences can be made based on hazard potential classification. Since approximately 80% of all Corps dams are high hazard, this factor provides minimal ability to differentiate between dams. It is expected that further research will result in better procedures for determining the importance of dams and those procedures may become part of this CI and Corps policy.

Many of the concepts introduced should be exposed to a broader range of engineers. Modifications to the procedure are certainly expected and suggestions are welcome. This report discusses no methodology for connecting the prevention (defense groups) and detection (monitoring devices) systems into a single product with comparable priority rankings. In actuality, software for support of this CI allows a tie to be made by assuming that the detection system has 15% of the importance of the prevention system. This assumption was based on the arbitrary decision that detection deficiencies should affect the overall dam condition by no more than one 15-point category. A second refinement not yet implemented would be to increase the priority rankings for monitoring devices based on the associated defense groups (and therefore adverse conditions) being in poor condition. The reasoning is that defense groups in poor condition need more monitoring. Needless to say, more could be done in this area.

It is recommended that other features of the project (structural, mechanical, electrical, etc.) be evaluated through parallel processes. Evaluation will allow quantitative comparisons of M&R priorities for all project features.

5.3 Implementation Status

A draft version of this technical report was printed in September 1998. It was distributed within the Corps for review and comments. During this review, CECW-E requested that publication of the document and any related training be withheld until they could complete a more thorough review. Written comments were obtained from CECW-EG and two meetings were held at which more edits were discussed. These comments and suggested edits were incorporated as received. The first meeting was with CECW-ET, CECW-EG, CECW-OM in February 1999. The second meeting in September 1999 was with CECW-EG, some members of the Embankment Dam Condition Index (CI) development team, and additional Division/District representatives. The edits and changes are included in the current technical report. The CECW-EG has indicated that the changes do not adequately address all issues, but they have been unable to identify the additional issues with the specificity necessary to make any changes. This is at least in part due to perceived conflicts with a CECW-E approach for incorporating risk assessment into the dam safety program that has yet to be developed.

As a technical report, this document is intended to be a summary of research results. The results include a product that can be used by Districts and others outside the Corps. Current Corps guidance on the use of CIs includes no references to embankment dams or flood control projects. At this time, therefore, each decision maker must individually determine if and how the Embankment Dam CI can assist in the management and safety of their embankment dams. Training workshops have been held in four districts with good to excellent results. Hydro-Québec is implementing this CI for all their embankment dams. These activities indicate a previously unmet need that this tool helps to address. As with any research product, it may or may not adequately meet user needs in either the short or long term. Additionally, other tools and procedures developed in the future may prove preferable.

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Appendix A: Examples of Prioritization of M&R Activities

A.0 Introduction

In this appendix, the proposed ranking systems are used to analyze and rank maintenance activities on three dams: (1) Lewisville (USACE), (2) TA-26A (Hydro-Québec), and (3) TA-24 (Hydro-Québec).

A.1 Lewisville

The dam is in Denton County, Texas, on the Elm Fork of the Trinity River, about 1 mile north of Lewisville, Texas. The dam is primarily for flood control, water conservation, and recreation. It provides flood protection to the leveed area of the city of Dallas and a dependable supply of water for municipal use. Table A.1.1 lists additional technical data for the Lewisville Dam. Tables A.1.2 and A.1.3 list monitoring instruments and dam attributes, respectively.

Table A.1.1. Technical data for Lewisville Dam.

Top elevation	:	560 ft
Top length (including spillway)	:	32,888 ft
Type	:	Rolled-earth fill embankment
Width of crown	:	20 ft
Max. height above stream bed	:	125 ft
Date of construction	:	1955
Seismicity	:	Low
Upstream slope protection	:	Rock (dumped)
Downstream slope protection	:	Grass
Spillway type	:	Uncontrolled, off-channel concrete gravity
Foundation (Western portion)	:	Sandstone/shale (Woodbine) with a sand and gravel overburden
Foundation (Eastern portion)	:	Clay shale

Notes: The project was constructed for the purpose of flood control and water conservation. Recreation was later added as a project purpose. The dam consists of three main features: a rolled-earth fill embankment 32,888-ft long, including the spillway; a 560-ft uncontrolled, off-channel, concrete gravity spillway with ogee weir section and crest at elevation 532 ft; and an outlet works consisting of the approach channel, intake structure, conduit conservation outlets, stilling basin, and outlet channel.

Table A.1.2. Monitoring instruments at Lewisville (being monitored).

Embankment:		
Settlement pins on bridge	:	6
Toe drains	:	5
Foundation:		
Piezometers	:	19
Relief wells	:	9

Table A.1.3. Summary of dam attributes.

Positive Attributes:

- Adequate upstream slope protection
- Regularly monitored
- Presence of relief wells and piezometers

Negative Attributes:

- Wet areas downstream
- Some depressions on downstream slope
- No internal piping control system
- Never been tested at full pool
- Pore pressure at design pool would exceed design standards; safety factor would be marginal
- Presence of several surface slides. However, these have been occurring on a regular basis and are under control
- Heavy vegetation in downstream toe area

Step 1: Importance of Embankment Dam

A relative importance score of 100 is assigned to Lewisville Dam based on Table 3.1.

A.1.1 Priority Ranking of Defense Groups

Step 2: Relative Likelihood of Failure Modes

Question One:

Given your understanding of the characteristics of the dam, the foundation conditions, performance history, and the potential loads, if you were informed that the dam had failed resulting in an uncontrolled release of the reservoir, what would your opinion be as to the probability that the failure mode being considered was the initiating mode of failure (assuming any component can potentially fail)?

Failures modes

Table A.1.4 lists relative likelihood of failure for failure modes at the Lewisville Dam.

Table A.1.4. Relative likelihood of failure.

Failure Mode	Relative Likelihood of Failure
1. Overtopping	$I[FM_1]$ = 10 %
2. Surface Erosion	$I[FM_2]$ = 0 %
3. Piping	$I[FM_3]$ = 70 %
4. Mass Movement	$I[FM_4]$ = 20 %
SUM	100%

Overtopping (10%)

- The spillway can accommodate the design flood
- There is no significant risk of blockage of the spillway channel
- There is a slight probability of overtopping triggered by surface slides at high pool.

Surface erosion (0%)

- The dam operates at a very low reservoir level; and the fetch is very small; therefore, the erosion of the upstream slope due to wave action is unlikely. Consequently the surface erosion failure mode (I=0) is not considered as a likely scenario for failure.

Piping (70%)

- Lack of an internal piping control system and the presence of erodable foundation materials make piping the most probable failure mode (I=70%)

Mass movement (20%)

- On the western portion, the dam is sitting on a sandstone/shale foundation, and on the eastern portion, on clay shale formations with a low shear strength
- Mass movement through the embankment and foundation is possible in areas of high pore pressures in the downstream toe area.

Step 3: Relative Likelihood of Adverse Conditions

Question Two:

Considering the failure mode, what is the relative importance of each adverse condition? (See Table A.1.5.)

Table A.1.5. Relative importance of the adverse conditions.

	Failure Modes				
	Overtopping	Surface Erosion	Piping	Mass Movement	Importance of Adverse Conditions
Adverse Conditions	$I[FM_1]$ (10%)	$I[FM_2]$ (0%)	$I[FM_3]$ (70%)	$I[FM_4]$ (20%)	$I[AC_i]$
1. Inadequate spillway capacity $I[AC_1, FM]$	0.30				0.03
2. Loss of spillway by erosion $I[AC_2, FM]$		-			-
3. Loss of crest elevation $I[AC_3, FM]$	0.70				0.07
4. Loss of surface protection material $I[AC_4, FM]$					
5. Piping of embankment materials $I[AC_5, FM]$			0.20		0.14
6. Piping of foundation materials $I[AC_6, FM]$			0.80		0.56
7. Slide through embankment (static or dynamic) $I[AC_7, FM]$				0.40	0.08
8. Slide through foundation and embank ment (static or dynamic) $I[AC_8, FM]$				0.60	0.12
Normalized SUM	1.0	1.0	1.0	1.0	1.0

Step 4: Importance of Defense Groups

For example, the most important defense group for the prevention of piping of foundation material is filtering in the foundation, followed by pressure control in the foundation. The first line of defense includes components that limit the buildup of pore pressures at critical locations (core, slurry walls, relief wells, finger drains, toe drain, etc). The second line of defense includes components (filter, inverted filter, etc) that act as a system to prevent the migration of particles through the embankment and the foundation. Table A.1.6 lists the relative importance of defense groups.

Table A.1.6. Relative importance of defense groups.

	Adverse Conditions								
	Inadequate Spillway Capacity	Loss of Spillway by Erosion	Loss of Crest Elevation	Loss of Surface	Piping of	Piping of Foundation Soils	Slide Through Embankment	Slide Through Foundation and Emb.	
Defense Groups	$I[AC_1]$ (0.03)	$I[AC_2]$ (-)	$I[AC_3]$ (0.07)	$I[AC_4]$ (-)	$I[AC_5]$ (0.1)	$I[AC_6]$ (0.56)	$I[AC_7]$(0.08)	$I[AC_8]$ (0.12)	$I[DG_k]$
1. Spillway Capacity $I[DG_1, AC]$	1.0								0.07
2. Spillway Erodability $I[DG_2, AC]$									
3. Crest Elevation $I[DG_3, AC]$			1.0						0.03
4. Surface Runoff and Collection/Discharge $I[DG_4, AC]$									
5. D/S Slope Protection $I[DG_5, AC]$									
6. U/S Slope Protection $I[DG_6, AC]$									
7. Filtering in Embankment $I[DG_7, AC]$					1.0		0.3		0.16
8. Pressure Control in Embankment $I[DG_8, AC]$							0.7	0.1	0.07
9. Filtering in Foundation $I[DG_9, AC]$						0.8		0.4	0.50
10. Pressure Control in Foundation $I[DG_{10}, AC]$						0.2		0.5	0.17
Normalized SUM	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Step 5: Determination of Defense Group Condition

Condition Definition for Pressure Control in Embankment: 70

During inspection, some localized soft/wet areas were detected on the downstream slope indicating zones of uncontrolled surface seepage; therefore, the condition of the pressure control in the embankment defense group was assigned a value of 70.

Condition Definition for Filtering in Foundation: 40

Evidence of prior occurrence of turbid flow indicates that filtering in the foundation is inadequate (CI=40).

Condition Definition for Pressure Control in Foundation: 10

Piezometric levels in the foundation were above design levels and were increasing; furthermore, soft/wet areas with increasing flows, or uncontrolled surface seepage, were observed. These indicators are symptoms of a deficient pressure control system in the foundation (CI=10).

Step 6: Ranking of Defense Groups for Lewisville Dam

The most serious deficiency in the defense groups at Lewisville Dam is pressure control in the foundation. Filtering ability for the foundation also has a high priority ranking. Repairs to correct either problem would probably be developed to address both problems. If so, the two priority rankings could be summed when comparing these rankings to other dams.

Step 7: Calculation of Overall CI for the Dam Defense System

The overall CI for the Dam Defense System is calculated in accordance with Equation 2.2 and is 52.6 for Lewisville Dam as shown in Table A.1.7.

Table A.1.7. Priority ranking calculation of defense groups.

	Importance		CI	
Defense Groups	I_{ED}	I_{DG}	CI_{DG}	PR_{DG} [(a)]
1. Spillway Capacity [DG_1]	0.785	0.07	100	-
2. Spillway Erodability [DG_2]				
3. Crest elevation [DG_3]	0.785	0.03	100	-
4. Surface runoff collection/discharge system [DG_4]				
5. D/S slope protection [DG_5]				
6. U/S slope protection [DG_6]				
7. Filtering in embankment [DG_7]	0.785	0.16	100	-
8. Pressure control in embankment [DG_8]	0.785	0.07	70	1.65
9. Filtering in foundation [DG_9]	0.785	0.50	40	23.55
10. Pressure control in foundation [DG_{10}]	0.785	0.17	10	12.01
SUM		1.0		
Overall Condition Index [CI_{dam}] [(b)] Defense Groups			52.6	

[(a)] From Equation 2.1

$$PR_{DGi} = I_{Dam} \cdot I_{DGi} \cdot \frac{(100 - CI_{DGi})}{(100)}$$

[(b)] Equation 2.2

$$CI_{Dam\,j} = \sum_{i=1}^{N_{DG}} I_{DGi,j} \bullet CI_{DGi,j}$$

A.1.3 Priority Ranking of Monitoring Devices

Step 8: Relative Importance of Indicators

Question One:

Considering each adverse condition, what is the relative value of that indicator for monitoring?

Refer to Table A.1.8 for the results of the coding for Question One.

Table A.1.8. Relative importance of indicators.

Indicators	Adverse Conditions: Inadequate Spillway Capacity $f[AC_1]$ (0.07)	Loss of Spillway by Erosion $f[AC_2]$	Loss of Crest Elevation $f[AC_3]$ (0.03)	Loss of Surface Protection $f[AC_4]$	Piping of Embankment $f[AC_5]$ (0.14)	Piping of Foundation $f[AC_6]$ (0.56)	Slide Through Embankment $f[AC_7]$ (0.08)	Slide Through Found. and Emb. $f[AC_8]$ (0.12)	Importance of Indicators $f[Ind_k]$
1. PL in foundation [Ind_1 AC]						0.10		0.50	0.116
2. PL in embankment [Ind_2 AC]					0.10		0.60	0.20	0.086
3. Uncontrolled seepage (D/S slope area) [Ind_3 AC]					0.50				0.07
4. Uncontrolled seepage (D/S toe) [Ind_4 AC]						0.50			0.28
5. Spillway cross-section and erosion of spillway [Ind_5 AC]	1.0								0.07
6. Change in geometry (crest) [Ind_6 AC]			1.0						0.03
7. Change in geometry (D/S slope) [Ind_7 AC]					0.4		0.4		0.088
8. Change in geometry (U/S slope) [Ind_8 AC]									
9. Change in geometry (D/S toe area) [Ind_9 AC]						0.40		0.30	0.26
10. Change in controlled seepage [Ind_{10} AC]									
11. Change in surface vegetation (D/S slope) [Ind_{11} AC]									
12. Change in surface vegetation (D/S toe area) [Ind_{12} AC]									
13. Change in geometry (relative movement fixed and floating components) [Ind_{13} AC]									
14. Ponding [Ind_{14} AC]									
Normalized SUM	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Step 9: Importance of Monitoring Devices

Question Two:

Considering each indicator, what is the relative value of each monitoring device?

Refer to Table A.1.9 for the results of the coding for Question Two.

Step 10: Determination of Monitoring Device Condition

The condition of the monitoring devices is determined from an onsite inspection using Table 3.5. The results of this inspection are included in Table A.1.10. Note that a CI = 33 for the piezometer in the foundation indicates that 1/3 of them have a CI = 0 (not functioning).

Step 11: Calculation of Priority Ranking for Monitoring Devices

The priority ranking for the monitoring devices is calculated according to Equation 2.3. The results are presented in Table A.1.10. The downstream toe area has a very high priority ranking of 45.1.

Step 12: Calculation of Overall CI for the Dam Monitoring System

The overall CI for the dam monitoring system is calculated in accordance with Equation 2.4 and is 31.92 for the Lewisville Dam.

Table A.1.9. Relative importance of monitoring devices (Lewisville Dam).

	Indicators of Adverse Condition														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Monitoring Devices	I[Ind] (0.116)	I[Ind] (0.086)	I[Ind] (0.07)	I[Ind] (0.28)	I[Ind] (0.07)	I[Ind] (0.03)	I[Ind] (0.088)	I[Ind]	I[Ind] (0.260)	I[Ind]	I[Ind]	I[Ind]	I[Ind]	I[Ind]	$I[MD_i]$
1.a Piezometers in foundation	0.70														0.081
1.b Piezometers in embankment		0.60													0.052
2. Flow Observations at relief wells															
3. Surface Monuments															
4. Settlement pins															
5. Flow observation at toe drain															
6. Downstream toe area	0.30			1.0					1.0						0.575
7. Downstream slope area		0.40	1.0				1.0								0.192
8. Crest and shoulders						1.0									0.03
9. Upstream slope															
10. Surface boundaries (outflow works)															
11. Surface boundaries (spillway)					1.0										0.07
12. Spillway training wall															
13. Abutment surfaces															
14. Slope inclinometers (location)															
15. Weirs															
16. Proposed devices															
Normalized Sum	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table A.1.10. Priority ranking calculation of monitoring devices.

	Importance		CI	
Monitoring Devices	I_{ED}	I_{MD}	CI_{MD}	PR_{MD} [(a)]
1.a Piezometer in foundation	0.785	0.0812	33	4.27
1.b Piezometer in embankment	0.785	0.0516	0	4.05
2. Flow observations at relief wells				
3. Surface monuments (markers)				
4. Settlement pins on bridge				
5. Flow observation at toe drain				
6. Downstream toe area	0.785	0.5748	0	45.1
7. Downstream slope area	0.785	0.1924	100	0
8. Crest and shoulders	0.785	0.03	100	0
9. Upstream slope				
10. Surface at boundary between dissimilar materials (outflow)				
11. Surface at boundary between dissimilar materials (spillway)	0.785	0.07	100	0
12. Spillway training wall				
13. Abutment surfaces				
14. Slope inclinometer				
15. Weirs				
16. Proposed devices				
SUM		1.0		
Monitoring CI [(b)]			31.92	

[(a)] From Equation 2.3

$$PR_{MDi} = I_{Dam} \cdot I_{MDi} \cdot \frac{(100 - CI_{MDi})}{100}$$

[(b)] From Equation 2.4

$$CI_{MS} = \sum_{i=1}^{N_{MD}} I_{MDi} \cdot CI_{MDi}$$

A.2 TA-26A Dam (Hydro-Québec)

A.2.1 Description

The TA-26A dam is owned and operated by Hydro-Québec and is part of the La Grande hydroelectric complex located in the James Bay region. The dam is built in a deep and narrow river valley filled with pervious heterogeneous material. The general area is of low seismicity (background level) and of moderate rain patterns (no hurricanes). Tables A.2.1 through A.2.3 list technical data, monitoring instruments, and attributes for dam TA-26A.

A.2.1. Technical data for dam TA-26A.

Embankment:		
Type of dam	:	Zoned earthfill with a central impervious core
Total length	:	541 ft
Nominal crest elevation	:	850 ft
Freeboard	:	10 ft
Camber (at max. section)	:	1.25 ft
Max. ht above stripped streambed	:	126 ft
Crest width	:	25 ft
Upstream slope	:	2.25H:1V to 2.5H:1V
Downstream slope	:	2.0H:1V to 2.25H:1V
Dam volume	:	340 000 cu. yds
Impervious core material	:	Moraine
Downstream filter material	:	Processed sand and gravel
Upstream/downstream shell material	:	Pervious moraine/random sand and gravel
Upstream slope protection	:	Riprap
Downstream slope protection	:	Coarse gravel
Date of completion	:	1979
Maximum operation level	:	840 ft
Minimum operation level	:	800 ft
Tailwater elevation	:	788 ft
Net head (max.)	:	52 ft

Foundation:			
Left and right abutments	Material	:	Bedrock (steep rock faces)
	Seepage control	:	Impervious core founded on treated rock
Riverbed (center of valley)	Material	:	Pervious heterogeneous overburden down to El. 610 ft
	Seepage control	:	Concrete cutoff wall, plus a short impervious blanket underneath the upstream shell
Concrete cutoff wall	Maximum depth	:	139 ft
	Width	:	2 ft
	Length (top of wall)	:	150 ft
	Total area	:	10,800 sq ft
Filtering and drainage	Blanket filter and drain underneath the downstream shell, plus a stone-filled drainage trench at the downstream toe		

A.2.2. Monitoring instruments at dam TA-26A (being monitored).

Embankment:		
Standpipe piezometers	:	2
Sealed piezometres	:	6
Surface monuments	:	3
Foundation:		
Standpipe piezometers	:	2
Sealed piezometers	:	13

A.2.3. Summary of dam attributes.

Positive Attributes:

- Pervious downstream shell
- Filters designed according to modern practice
- Dense overburden foundation material
- Coarse toe drain (drainage trench)
- Porewater pressures monitored underneath downstream shell
- Sheltered from large wave attack

Negative Attributes:

- Defective cutoff wall in pervious foundation
- Downstream toe area completely submerged
- Seepage cannot be located nor monitored

A.2.2 Priority Ranking of Defense Groups

Step 1: Importance of the Embankment Dam

From the dam classification system in use at Hydro-Québec, dam TA-26A has a score of 79, which is 24.5% of the maximum score (322) in the present dam inventory. The relative importance factor for dam TA-26A is therefore 24.5.

Step 2: Relative Likelihood of Failures Modes

Question One:

Given your understanding of the characteristics of the dam, the foundation conditions, performance history, and the potential loads, if you were informed that the dam had failed resulting in an uncontrolled release of the reservoir, what would your opinion be as to the probability that the failure mode being considered was the initiating mode of failure (assuming any component can potentially fail)?

Failure modes

Table A.2.4 lists relative likelihood of failure for failure modes at Dam TA-26A.

A.2.4. Relative likelihood of failure

Failure Mode	Relative Likelihood of Failure
1. Overtopping	$l[FM_1] = 0\ \%$
2. Surface Erosion	$l[FM_2] = 0\ \%$
3. Piping	$l[FM_3] = 90\ \%$
4. Mass Movement	$l[FM_4] = 10\ \%$
SUM	100%

Overtopping (0%)

Not considered as a likely (pF < 10%) failure mode since:

- Present spillway capacity can accommodate the design flood
- There in no significant risk of blockage of spillway channel
- No substantial crest settlement is anticipated in case of an earthquake because of dense foundation materials.

Surface erosion (0%)

Not considered as a likely (pF < 10%) failure mode since:

- The dam is sheltered from large wave attack (small fetch)
- The downstream slope protection material is adequate to resist erosion from the design precipitation.

Piping (90%)

- Piping through the embankment is considered unlikely (pF < 10%) since the filters are designed according to modern practice
- Piping of the foundation material is possible only in a small area beyond the downstream toe where the foundation material is exposed. Large seepage quantities due to the defective cutoff wall could generate larger than anticipated exit gradients in this specific area.

Mass movement (10%)

- Mass movement of the embankment (either in the upstream or downstream shell) is considered unlikely (pF < 10%) since fill materials are dense and strong, and observed pore water pressures are within design assumptions
- Mass movement through the embankment and foundation is possible since large pore water pressures can develop downstream due to the defective cutoff wall. However, the probability of this failure mode is approximately one order of magnitude smaller than the probability of failure associated with piping of foundation soils beyond the downstream toe.

Step 3: Relative Likelihood of Adverse Conditions

Question Two:

Considering the failure mode, what is the relative importance of each adverse condition? (See Table A.2.5.)

A.2.5. Relative importance of the adverse conditions.

	Failure Modes				Importance of Adverse Conditions
	Overtopping	Surface Erosion	Piping	Mass Movement	
Adverse Conditions	f[FM_1] (0%)	f[FM_2] (0%)	f[FM_3] (90%)	f[FM_4] (10%)	f[AC]
1. Inadequate spillway capacity f[AC_1 FM]	-				-
2. Loss of spillway by erosion f[AC_2 FM]		-			-
3. Loss of crest elevation f[AC_3 FM]	-				
4. Loss of surface protection material f[AC_4 FM]		-			-
5. Piping of embankment materials f[AC_5 FM]			0		0
6. Piping of foundation soils f[AC_6 FM]			1.0		0.90
7. Slide through embankment (static or dynamic) f[AC_7 FM]				0	0
8. Slide through foundation and embankment (static or dynamic) f[AC_8 FM]				1.0	0.10
Normalized SUM	1.0	1.0	1.0	1.0	1.0

Step 4: Importance of Defense Groups

Question Three:

What is the relative importance of the each defense group in preventing the adverse condition?

Refer to Table A.2.6. Failure by piping in foundation soils can be prevented by the combined action of two different defense groups:

- Filtering in Foundation
- Pressure Control in Foundation.

A.2.6. Relative importance of defense groups.

	Adverse Conditions								Importance of Defense Groups
	Inadequate Spillway Capacity		Loss of Surface Protection			Piping of Foundation Soils			
Defense Groups	$I[AC_1]$ (-)	$I[AC_2]$ (-)	$I[AC_3]$ (-)	$I[AC_4]$ (-)	$I[AC_5]$ (-)	$I[AC_6]$ (0.9)	$I[AC_7]$ (-)	$I[AC_8]$ (0.1)	$I[DG_i]$
1. Spillway Capacity $I[DG, AC]$	-								-
2. Spillway Erodability $I[DG, AC]$		-							-
3. Crest Elevation $I[DG, AC]$			1.0						-
4. Surface Runoff and Collection/Discharge $I[DG, AC]$				-					-
5. D/S Slope Protection $I[DG, AC]$				-					-
6. U/S Slope Protection $I[DG, AC]$				-					-
7. Filtering in Embankment $I[DG, AC]$					-		-		-
8. Pressure Control in Embankment $I[DG, AC]$					-		-	0.20	0.02
9. Filtering in Foundation $I[DG, AC]$						0.80		-	0.72
10. Pressure Control in Foundation $I[DG, AC]$						0.20		0.80	0.26
Normalized SUM	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

An efficient filter is the most effective protection against piping; however, particle movement is only possible in the presence of pore water pressure (seepage velocity). Thus controlling the level of porewater pressure would also assist to some extent in preventing piping. Considering the dam geometry and foundation conditions, the relative importance of the Filtering Defense Group in Foundation is estimated at 80%, as compared to 20% to the importance of Pressure Control Defense Group in Foundation.

Failure by mass instability of the embankment and supporting foundation soils can be prevented by the combined action of two defense groups:

- Pressure Control in Embankment
- Pressure Control in Foundation.

The relative importance of the two defense groups can be evaluated on the basis of their relative contribution to the total shear resistance along a given failure surface. For this specific dam, the foundation soil contributes to a larger (~80%) extent to the overall stability than does the embankment (~20%).

Step 5: Determination of Defense Group Condition

Condition Definition for Pressure Control in Embankment: 100

Based on current piezometer readings, pore water pressures in the impervious core are judged to be consistent with design assumptions. The vibrating wire-sealed piezometers have recorded a slight pressure increase as a function of time. However, this increase is most probably due to creep of the vibrating wire. As a consequence, Pressure Control in Embankment is rated at 100.

Condition Definition for Filtering in Foundation: 60

The downstream toe area is permanently submerged by 60 ft of water and can be inspected only by divers. Although the last underwater inspection did not reveal any evidence of piping (no indicators of distress), this defense group cannot be considered perfect and its condition should be rated below 100%. As the downstream toe area is not fully protected against piping (considered a known defect in this case since the area cannot be inspected routinely), the condition is described as fair (CI=60) while the function of the defense group is not

significantly affected. There are large flow quantities due to a defective cutoff. No weighted berm exists beyond the downstream toe of the dam.

Condition Definition for Pressure Control in Foundation: 80

The defective cutoff wall allows significant pore water pressures to be transmitted underneath the downstream shell. Therefore, the condition of this defense group cannot be considered perfect, although the safety factor against sliding is still adequate. The defective cutoff is considered only as a minor defect relative to the stability of the downstream shell and foundation since a second line of defense (short impervious upstream blanket) mitigates the poor performance of the cutoff wall. A condition rating of 80 is considered appropriate in this case.

Step 6: Calculation of Priority Ranking for Defense Groups

The most serious deficiency in defense groups at dam TA-26A is the filtering capacity in the foundation soils (PRDG 7.1), namely, at the downstream toe of the dam. Defects in pressure control in foundation are much less critical with a PRDG 1.3. These rankings should be compared with other dams within Hydro-Québec.

Step 7: Calculation of Overall CI for the Dam Defense System

The overall condition index of dam TA-26A based on the condition and importance of the defense groups is 66 and is calculated on Table A.2.7 in accordance with Equation 2.2.

A.2.7. Priority ranking calculation of defense groups (Dam TA-26A).

Defense Groups	Importance		CI	
	I_{ED}	I_{DG}	CI_{DG}	PR_{DG} [a]
1. Spillway Capacity [DG_1]				
2. Spillway Erodability [DG_2]				
3. Crest elevation [DG_3]				
4. Surface runoff collection/discharge system [DG_4]				
5. D/S slope protection [DG_5]				
6. U/S slope protection [DG_6]				
7. Filtering in embankment [DG_7]				
8. Pressure control in embankment [DG_8]	0.245	0.02	100	
9. Filtering in foundation [DG_9]	0.245	0.72	60	7.056
10. Pressure control in foundation [DG_{10}]	0.245	0.26	80	1.274
SUM		1.0		
Overall Condition Index [CI_{dam}] [b] Defense Groups			66	

[a] From Equation 2.1

$$PR_{DGi} = I_{Dam} \cdot I_{DGi} \cdot \frac{(100 - CI_{DGi})}{(100)}$$

[b] Equation 2.2

$$CI_{Dam\,j} = \sum_{i=1}^{N_{DG}} I_{DGi,j} \bullet CI_{DGi,j}$$

A.2.3 Priority Ranking of Monitoring Devices

Step 8: Importance of Indicators

Question One:

Considering each adverse condition, what is the relative value of that indicator for monitoring? (See Table A.2.8.)

Only two out of eight adverse conditions have non-zero relative importance, namely:

- Piping of Foundation Soils
- Slide through Foundation and Embankment.

Indicators for Piping of Foundation Soils:

The most significant indicator for the occurrence of piping is the presence of turbid flow in the downstream toe area (indicator 4). However, the onset of piping can sometimes be deduced by computing exit gradients from measurements of pore water pressures in the foundation (indicator 1). Finally, eroded materials accumulated locally in the form of sand boils in the downstream toe area (indicator 9) are indicative of piping in its final stage of development.

The relative importance of these three indicators is therefore assigned as follows:

Indicators for piping in foundation		Relative Importance (normalized to 1.0)
1	Piezometric levels in foundation	0.3
4	Uncontrolled seepage (clear or turbid flow)	0.6
9	Change in geometry at downstream toe	0.1

Indicators for Slide Through Embankment and Foundation:

The most significant indicator of the occurrence of a slide through the embankment and foundation is relative movement, i.e., changes in geometry (crest (6), downstream slope (7), and downstream toe area (9)). However, prior to actual mass movements, the onset of instabilities can be predicted by computing safety factors on the basis of measured pore water pressures in the embankment and foundation (indicators 1 and 2).

The relative importance of these indicators is estimated as follows:

Indicators for sliding in foundation and embankment		Relative Importance (normalized to 1.0)
2	Piezometric levels in foundation	0.4
2	Piezometric levels in embankment	0.1
6	Change in geometry at crest	0.1
7	Change in geometry at downstream slope	0.3
9	Change in geometry at downstream toe area	0.1

The most important indicator is the presence of turbid flow (Indicator 4 - IIND=0.54), followed by piezometric levels in the foundation (Indicator 1 - IIND=0.31).

A.2.8. Relative importance of indicators.

Indicators	Adverse Conditions: Inadequate Spillway Capacity $I[AC_1]$	Loss of Spillway by Erosion $I[AC_2]$	Loss of Crest Elevation $I[AC_3]$	Loss of Surface Protection $I[AC_4]$	Piping of Embankment $I[AC_5]$	Piping of Foundation Soils $I[AC_6]$ (0.9)	Slide Through Embankment $I[AC_7]$	$I[AC_8]$ (0.1)	$I[Ind_i]$
1. PL in foundation $[Ind_1\ AC]$						0.3		0.4	0.31
2. PL in embankment $[Ind_2\ AC]$								0.1	0.01
3. Uncontrolled seepage (D/S slope area) $[Ind_3\ AC]$									
4. Uncontrolled seepage (D/S toe) $[Ind_4\ AC]$						0.6			0.54
5. Spillway cross-section and erosion of spillway $[Ind_5\ AC]$	1.0	1.0							
6. Change in geometry (crest) $[Ind_6\ AC]$								0.1	0.01
7. Change in geometry (D/S slope) $[Ind_7\ AC]$								0.3	0.03
8. Change in geometry (U/S slope) $[Ind_8\ AC]$									
9. Change in geometry (D/S toe area) $[Ind_9\ AC]$						0.1		0.1	0.1
10. Change in controlled seepage $[Ind_{10}\ AC]$									
11. Change in surface vegetation (D/S slope) $[Ind_{11}\ AC]$									
12. Change in surface vegetation (D/S toe area) $[Ind_{12}\ AC]$									
13. Change in geometry (relative movement fixed and floating components) $[Ind_{13}\ AC]$									
14. Ponding $[Ind_{14}\ AC]$									
Normalized SUM	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Step 9: Importance of Monitoring Devices

Question Two:

Considering each indicator, what is the relative value of each monitoring device?

There are five types of monitoring devices that can provide information on the indicators; two are instruments (piezometers and surface monuments) and three are inspection surfaces (crest, downstream slope, and downstream toe area). Piezometers are further subdivided according to their type (standpipe or sealed). The exposed and submerged portions of the downstream slope are also considered as separate observation surfaces. Refer to Table A.2.9 for the results of the coding for Question Two.

Piezometric levels in foundation:

Standpipe piezometers are located in proximity to the downstream toe of the dam and are considered to be more informative (60%) than other piezometers in the foundation (40%).

Piezometric levels in embankment:

The standpipe piezometers installed in the embankment are located close to the crest of the dam and are dry part of the time (10%). Sealed piezometers are installed at greater depths and provide more useful information (90%).

Change of geometry at the crest:

Changes of geometry at the crest can be evaluated by visual inspections of the crest and the shoulders (80%) and by surveying surface monuments (20%). The surface monuments have a lower rating than the crest and shoulders because they provide information at only a set of discrete points along the crest of the dam.

Change of geometry at the downstream toe area:

The relative importance of the submerged (50%) and exposed (50%) portions of the downstream slope is assigned in proportion to their total area.

A.2.9. Relative importance of monitoring devices (Dam TA-26A).

	Indicators of Adverse Condition														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Monitoring Devices	$I[Ind_1]$ 0.31	$I[Ind_2]$ 0.01	$I[Ind_3]$	$I[Ind_4]$ 0.54	$I[Ind_5]$	$I[Ind_6]$ 0.01	$I[Ind_7]$ 0.03	$I[Ind_8]$	$I[Ind_9]$ 0.10	$I[Ind_{10}]$	$I[Ind_{11}]$	$I[Ind_{12}]$	$I[Ind_{13}]$	$I[Ind_{14}]$	$I[MD]$
1.a Piezometers (standpipe)	0.6	0.1													0.187
1.b Piezometers (sealed)	0.4	0.4													0.133
2. Flow Observations at relief wells						0.2									0.002
3. Surface Monuments															
4. Settlement pins															
5. Flow observation at toe drain															
6. Downstream toe area				1.0					1.0						0.640
7.a Downstream slope area (exposed)							0.5								0.015
7.b Downstream slope area (submerged)							0.5								0.015
8. Crest and shoulders						0.8									0.008
9. Upstream slope															
10. Surface boundaries (outflow works)															
11. Surface boundaries (spillway)															
12. Spillway training wall															
13. Abutment surfaces															
14. Slope inclinometers (location)															
15. Weirs															
16. Proposed devices															
Normalized Sum	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Step 10: Determination of Monitoring Device Condition

The monitoring device conditions are determined from an onsité inspection using Table 3.5. The results are presented in Table A.2.10.

A.2.10. Priority ranking calculation of monitoring devices.

Monitoring Devices	I_{ED}	I_{MD}	CI_{MD}	PR_{MD} [(a)]
1.a Piezometer (standpipe)	0.245	0.187	100	-
1.b Piezometer (sealed)	0.245	0.133	100	-
2. Flow observations at relief wells	0.245	0.002	100	-
3. Surface monuments (markers)				
4. Settlement pins on bridge				
5. Flow observation at toe drain				
6. Downstream toe area	0.245	0.64	0	15.68
7.a Downstream slope area (exposed)	0.245	0.015	100	-
7.b Downstream slope area (submerged)	0.245	0.015	0	0.37
8. Crest and shoulders	0.245	0.008	100	-
9. Upstream slope				
10. Surface at boundary between dissimilar materials (outflow)				
11. Surface at boundary between dissimilar materials (spillway)				
12. Spillway training wall				
13. Abutment surfaces				
14. Slope inclinometer				
15. Weirs				
16. Proposed devices				
SUM		1.0		
Monitoring CI [(b)]			34.5	

[(a)] From Equation 2.3

$$PR_{MDi} = I_{Dam} \cdot I_{MDi} \cdot \frac{(100 - CI_{MDi})}{100}$$

[(b)] From Equation 2.4

$$CI_{MS} = \sum_{i=1}^{N_{MD}} I_{MDi} \cdot CI_{MDi}$$

Note: Periodic (5- to 10-yr interval) underwater inspection by divers will be required in the downstream toe area.

Step 11: Calculation of Priority Ranking for Monitoring Devices

The downstream toe area is the most important inspection surface for dam TA-26A with a relative weight of 64%. Since it is totally submerged and cannot be inspected on a routine basis (CI=0), it is also the most critical device for this dam with a PRMD=15.7. This demonstrates the importance of periodic underwater inspections by divers. The priority rankings are included in Table A.2.10.

Step 12: Calculation of Overall CI for the Dam Monitoring System

The overall CI for monitoring devices at dam TA-26A is 35 in accordance with Equation 2.4.

A.3 TA-24 Dam (Hydro-Québec)

The TA-24 dam is owned and operated by Hydro-Québec and is part of the La Grande hydroelectric complex located in the James Bay Region. Tables A.3.1 through A.3.3 provide technical data, monitoring instruments, and summary of dam attributes for dam TA-24.

A.3.1. Technical data for dam TA-24.

Type of dam	:	Zoned rockfill dam, with a central impervious core
Total length	:	2490 ft
Nominal crest elevation	:	852 ft
Freeboard	:	12 ft
Camber (at max. section)	:	2 ft
Max. ht above stripped streambed	:	210 ft
Crest width	:	30 ft
Upstream slope	:	1.7H:1V
Downstream slope	:	1.6H:1V
Dam volume	:	2,765,000 cu yd
Impervious core material	:	Moraine
Upstream/downstream filter material	:	Processed sand and gravel
Upstream/downstream shell material	:	Quarried sound rock
Upstream slope protection	:	Riprap
Downstream slope protection	:	Random rockfill
Date of completion	:	1979
Maximum operation level	:	840 ft
Minimum operation level	:	800 ft
Foundation material	:	Massive rock
Foundation treatment	:	Standard surface preparation and treatment, plus curtain grouting

A.3.2. Monitoring instruments at dam TA-24 (being monitored).

Embankment:		
Standpipe piezometers	:	2
Sealed piezometres	:	7
Surface monuments	:	15
Slope inclinometer	:	1
Thermometers	:	27
Foundation:		
Sealed piezometers	:	1
Seepage measuring weirs (surface seepage)	:	1 (principal) + 2 (secondary)

A.3.3. Summary of dam attributes.

Positive Attributes:

- Founded on competent rock
- Central core sitting on bedrock
- Standard foundation preparation and grouting
- Pervious rockfill shells
- Filters designed according to modern practice
- Downstream toe area cleared and drained
- Seepage can be located and monitored

Negative attributes:

- Local zones of marginal or poor quality riprap (known defect)
- Poorly compacted core material around an instrument riser pipe (known defect)

Step 1: Importance of Embankment Dam

From the dam classification system in use at Hydro-Québec, dam TA-24 gets a score of 180, which is 55.9% of the maximum score (322) in the present dam inventory. The relative importance factor for dam TA-24 is therefore 55.9.

A.3.1 Priority Ranking of Defense Groups

Step 2: Relative Likelihood of Failure Modes

Question One:

Given your understanding of the characteristics of the dam, the foundation conditions, performance history, and the potential loads, if you were informed that the dam had failed resulting in an uncontrolled release of the reservoir, what

would your opinion be as to the probability that the failure mode being considered was the initiating mode of failure (assuming any component can potentially fail)?

Failures modes

Table A.3.4 lists relative likelihood of failure for failure modes at dam TA-24.

A.3.4. Relative likelihood of failure.

Failure Mode	Relative Likelihood of Failure
1. Overtopping	$l[FM_1] = 20\%$
2. Surface Erosion	$l[FM_2] = 80\%$
3. Piping	$l[FM_3] = 0\%$
4. Mass Movement	$l[FM_4] = 0\%$
SUM	100%

Overtopping (20%)

- A column of poorly compacted core material around a vertical riser pipe may lead to excessive internal settlements that may eventually reach the level of the crest. Depending on the size and the depth of the resulting crater, overtopping is possible if the reservoir is at its maximum elevation. However, considering that the downstream shell is pervious and resistant, breaching of the dam would occur slowly.

- On the other hand, the spillway capacity is not considered to be an issue (pF < 10%) since:
    - present spillway capacity can accommodate the design flood,
    - there in no significant risk of blockage of the spillway channel

Surface erosion (80%)

- Local zones on the upstream slope have marginal to poor quality riprap that can be damaged by the design storm wave. This failure mode is considered the most likely for this dam.

- Erosion of the downstream slope is not considered a likely failure mode for a rockfill shell.

Piping (0%)

- Piping through the embankment is considered unlikely (pF < 10%) since the filters are designed according to latest standards.
- Piping of the foundation material is considered unlikely (pF < 10%) given the good quality of the rock foundation.

Mass movement (0%)

- Mass movement of the embankment (either in the upstream or downstream shell) is considered unlikely (pF < 10%) since fill materials are dense and resistant, and porewater pressures are within design assumptions.
- Mass movement through the embankment and foundation is considered unlikely (pF < 10%) because of the good quality of the rock foundation.

Step 3: Relative Likelihood of Adverse Conditions

From the Table A.3.4, overtopping failure mode is considered only in connection with the loss of crest elevation (100%), whereas surface erosion failure mode would be applicable only to the upstream slope protection (100%).

Question Two:

Considering the failure mode, what is the relative importance of each adverse condition? (See Table A.3.5.)

Step 4: Importance of Defense Groups

The only defense groups associated with the above-mentioned failure modes and adverse conditions are:

Adverse Condition	Defense Group	Relevance
• Loss of Crest Elevation	Crest Elevation	100%
• Loss of Surface Protection	Upstream Slope Protection	100%

See Table A.3.6.

A.3.5. Relative importance of the adverse conditions.

	Failure Modes				
	Overtopping	Surface erosion	Piping	Mass Movement	Importance of Adverse
Adverse Conditions	$I[FM_1]$ (20%)	$I[FM_2]$ (80%)	$I[FM_3]$ (- %)	$I[FM_4]$ (- %)	$I[AC_i]$
1. Inadequate spillway capacity $I[AC_1, FM]$	-				-
2. Loss of spillway by erosion $I[AC_2, FM]$		-			-
3. Loss of crest elevation $I[AC_3, FM]$	1.0				0.2
4. Loss of surface protection material $I[AC_4, FM]$		1.0			0.8
5. Piping of embankment materials $I[AC_5, FM]$			0		0
6. Piping of foundation soils $I[AC_6, FM]$			0		0
7. Slide through embankment (static or dynamic) $I[AC_7, FM]$				0	0
8. Slide through foundation and embankment (static or dynamic) $I[AC_8, FM]$				0	0
Normalized SUM	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Step 5: Determination of Defense Group Condition

Condition Definition for Crest Elevation: 70

The condition for the crest elevation is excellent, except in the immediate vicinity of the instrument riser where a sudden collapse could occur. The core material around the riser pipe is known to be poorly compacted and prone to sudden collapse. However, no differential settlement ever developed at the crest, almost 20 years after construction. This is then considered as a known defect. A condition rating of 70 is therefore assigned to the crest elevation defense group and no immediate action is required.

Condition Definition for Upstream Slope Protection: 70

The upstream slope protection at TA-24 experienced moderate erosion over the years, mainly as isolated losses of the outer layer of riprap. These damages were repaired recently. However, existing local zones of finer riprap that had not yet suffered deterioration were not upgraded. Despite their good performance up to now, these patches of finer rock would not resist the design storm

without major damage. On this basis, they are considered as known defects, with a rating of 70, as no immediate action is required.

Step 6: Calculation of Priority Ranking for Defense Groups

The most serious shortcoming in defense groups at dam TA-24 is the presence of patches of finer riprap in the upstream slope protection (PRDG=13.4). In comparison, the existence of a column of collapsible soil inside the impervious core is much less critical with a PRDG=3.4. These rankings should be compared with other dams within Hydro-Québec.

A.3.6. Relative importance of defense groups.

	Adverse Conditions								
	Inadequate Spillway Capacity	Loss of Spillway by Erosion	Loss of Crest Elevation	Loss of Surface Protection	Piping of Embankment	Piping of Foundation Soils	Slide Through Embankment	Slide Through Foundation &Emb	Importance of Defense Groups
Defense Groups	$I[AC]$	$I[AC]$	$I[AC]$	$I[AC]$	$I[AC]$	$I[AC]$ (0.9)	$I[AC]$	$I[AC]$ (0.1)	$I[Ind]$
1. Spillway capacity $I[DG_1, AC]$									
2. Spillway erodibility $I[DG_2, AC]$									
3. Crest Elevation $I[DG_3, AC]$			1.0						0.2
4. Surface Runoff and Collection/Discharge $I[DG, AC]$				1.0					0.8
5. D/S Slop Protection $I[DG_5, AC]$									
6. U/S Slop Protection $I[DG_6, AC]$									
7. Filtering in Embankment $I[DG_7, AC]$									
8. Pressure Control in Embankment $I[DG_8, AC]$									
9. Filtering in Foundation $I[DG_9, AC]$									
10. Pressure Control in Foundation $I[DC_{10}, AC]$									
Normalized SUM	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**

Step 7: Calculation of Overall CI for the Dam Defense System

The overall condition index of dam TA-24 based on evaluation of defense groups is 70 (see Table A.3.7).

A.3.7. Priority ranking calculation of defense groups.

	Importance		CI	
Defense Groups	I_{ED}	I_{DG}	CI_{DG}	PR_{DG} (1)
1. Spillway Capacity [DG_1]				
2. Spillway Erodability [DG_2]				
3. Crest elevation [DG_3]	0.559	0.2	70	3.354
4. Surface runoff collection/discharge system [DG_4]				
5. D/S slope protection [DG_5]				
6. U/S slope protection [DG_6]	0.559	0.8	70	13.416
7. Filtering in embankment [DG_7]				
8. Pressure control in embankment [DG_8]				
9. Filtering in foundation [DG_9]				
0. Pressure control in foundation [DG_{10}]				
SUM		1.0		
Overall Condition Index [CI_{dam}] (2) Defense Groups		-	70	

(1) From Equation 2.1

$$PR_{DGi} = I_{Dam} \cdot I_{DGi} \cdot \frac{(100 - CI_{DGi})}{(100)}$$

(2) Equation 2.2

$$CI_{Dam\,j} = \sum_{i=1}^{N_{DG}} I_{DGi,j} \bullet CI_{DGi,j}$$

A.3.2 Priority Ranking of Monitoring Devices

Step 8: Importance of Indicators

Only two out of eight adverse conditions have non-zero relative importance, namely:

- Loss of Crest Elevation
- Loss of Upstream Slope Protection.

Indicators for Loss of Crest Elevation and loss of Upstream Slope Protection:

The most significant indicators for these adverse conditions are changes in design geometry, and they can be monitored mostly by visual inspection. These indicators are specifically changes in the crest area (in the form of a crater) and changes in the upstream slope area (in the form of riprap erosion).

Question One:

Considering each adverse condition, what is the relative value of that indicator for monitoring? (See Table A.3.8.)

Step 9: Importance of Monitoring Devices

Question Two:

Considering each indicator, what is the relative value of each monitoring device?

The monitoring devices (or surfaces) associated with these indicators are obviously the corresponding areas, namely the crest area and the upstream slope area. None of the instruments available at TA-24 can give an early warning with respect to the above-mentioned adverse conditions. Their relative importance is therefore set at zero. Refer to Table A.3.9 for the results of the coding for Question Two.

Step 10: Determination of Monitoring Device Condition

Since both crest and upstream slope areas can be fully inspected, the condition index for these monitoring surfaces is a perfect 100.

Step 11: Calculation of Priority Ranking for Monitoring Devices (Dam TA-24)

All of the monitoring devices at Dam TA-24 are in perfect condition (CI = 100) and hence the priority rankings are zero. Table A.3.10 shows the priority rankings.

A.3.8. Relative importance of indicators.

	Adverse Conditions								
	Inadequate Spillway Capacity	Loss of Spillway by Erosion	Loss of Crest Elevation		Piping of Embankment	Piping of Foundation Soils	Slide Through Embankment	Slide Through Found & Emb.	Importance of Indicators
Indicators	*I* [*AC*]	*I* [AC_2]	*I* [AC_3] (0.2)	*I* [AC_4] (0.8)	*I* [AC_5]	*I* [AC_6]	*I* [AC_7]	*I* [AC_8]	*I* [Ind_k]
1. PL in foundation [Ind_1|*AC*]									
2. PL in embankment [Ind_1 *AC*]									
3. Uncontrolled seepage (D/S slope area) [Ind_2 *AC*]									
4. Uncontrolled seepage (D/S toe) [Ind_4 *AC*]									
5. Spillway cross-section and erosion of spillway [Ind_5 *AC*]	1.0	1.0							
6. Change in geometry (crest) [Ind_6 *AC*]			1.0					0	0.2
7. Change in geometry (D/S slope) [Ind_7 *AC*]									
8. Change in geometry (U/S slope) [Ind_8 *AC*]				1.0					0.8
9. Change in geometry (D/S toe area) [Ind_9 *AC*]									
10. Change in controlled seepage [Ind_{10} *AC*]									
11. Change in surface vegetation (D/S slope) [Ind_{11} *AC*]									
12. Change in surface vegetation (D/S toe area) [Ind_{12} *AC*]									
13. Change in geometry (relative movement fixed and floating components) [Ind_{13} *AC*]									
14. Ponding [Ind_{14} *AC*]									
Normalized SUM		**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	1.0	1.0	1.0

A.3.9. Relative Importance of monitoring devices (Dam TA-24).

	Indicators of Adverse Condition														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
Monitoring Devices	$I[Ind_1]$	$I[Ind_2]$	$I[Ind_3]$	$I[Ind_4]$	$I[Ind_5]$	$I[Ind_6]$ 0.2	$I[Ind_7]$	$I[Ind_8]$ 0.8	$I[Ind_9]$ 0.10	$I[Ind_{10}]$	$I[Ind_{11}]$	$I[Ind_{12}]$	$I[Ind_{13}]$	$I[Ind_{14}]$	$I[MD_i]$
1. Piezometers															
2. Flow Observations at relief wells															
3. Surface Monuments															
4. Settlement pins															
5. Flow observation at toe drain															
6. Downstream toe area															
7.Downstream slope area															
8. Crest and shoulders						1.0									0.2
9. Upstream slope								1.0							0.8
10. Surface boundaries (outflow works)															
11. Surface boundaries (spillway)															
12. Spillway training wall															
13. Abutment surfaces															
14. Slope inclinometers (location)															
15. Weirs															
16. Proposed devices															
Normalized Sum	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Step 12: Calculation of Overall CI for the Dam Monitoring System

This result does not imply that the existing instrumentation at this dam is useless. Some structures are specially instrumented to improve our knowledge about general behavior of dams, to document specific aspects, etc. If one of these specific instruments fails, it will probably not be replaced. Good practice calls also for regular inspection of all visible surfaces, not only those associated with the failure mode that is thought to be the most likely one. It is also good practice to install and maintain instrumentation to monitor some vital information, such as controlled seepage, irrespective of whether problems are anticipated.

A.3.10. Priority ranking calculation of monitoring devices.

	Importance		CI	
Monitoring Devices	I_{ED}	I_{MD}	CI_{MD}	PR_{MD} [a]
1. Piezometer				
2. Flow observations at relief wells				
3. Surface monuments (markers)				
4. Settlement pins on bridge				
5. Flow observation at toe drain				
6. Downstream toe area				
7. Downstream slope area				
8. Crest and shoulders	0.559	0.2	100	0
9. Upstream slope	0.559	0.8	100	0
10. Surface at boundary between dissimilar materials (outflow)				
11. Surface at boundary between dissimilar materials (spillway)				
12. Spillway training wall				
13. Abutment surfaces				
14. Slope inclinometer				
15. Weirs				
16. Proposed devices				
SUM		1.0		
Monitoring CI [b]			100	

[a] From Equation 2.3

$$PR_{MDi} = I_{Dam} \cdot I_{MDi} \cdot \frac{(100 - CI_{MDi})}{100}$$

[b] From Equation 2.4

$$CI_{MS} = \sum_{i=1}^{N_{MD}} I_{MDi} \cdot CI_{MDi}$$

Appendix B: Prototype for Risk of Failure and Hazard Potential Classification

The embankment dam importance factor described in Appendix A was developed for use in conjunction with the priority rankings. It was later determined that the factor should not be used in the condition indexing process. Nonetheless, it is retained for reference as it may provide some value in determining the priority of work on dams. Its greatest benefits may be as a reminder of some important prioritization considerations. The hazard potential described does not replace hazard categories by the Corps of Engineers Dam Safety Assurance Program (Engineer Regulation 1110-2-1155). It is expected that further research will result in better procedures for determining the importance of dams ar d those procedures may become part of this CI and Corps policy.

The importance factors described in this appendix are a modification of a pre-existing classification system developed by Hydro-Québec based on risk and consequences of dam failure in their publication "Risk of Failure and Hazard Potential Classification of Hydro-Québec Dams." Dams are classified based on point scores for risk and for hazard potential. Risk of failure and hazard potential are defined by 13 constant and variable parameters scored with a weighting system. These 13 parameters divide into three categories: the first two categories (constant physical parameters and variable parameters) describe the vulnerability of the dam, that is, the risk of failure; and the third category describes the consequences, that is, the hazards, of failure as life loss and property damage.

Point scores for each of these parameters are determined based on Tables B.1 through B.3 and combined for an overall score for the dam. Parameters A_6 and B_6 are not completed but provide the basic information to be considered. A form for recording dam importance information is included in Figure B.1. An example form has been filled out for Lewisville Dam in Figure B.2. Dam vulnerability (V) is the sum of the arithmetic mean of the scores for the physical constants (A) added to the arithmetic mean of the scores of the variables (B):

$$V = A + B$$

Dam class is determined from a classification scale based on the overall score (S), that is, the sum of vulnerability (V) and three times the score of the hazard potential parameter (C). The sum is divided by 50 to normalize the scoring range:

$$S = (V + 3C) / 50$$

Table B.1. Classification parameters for physical constants.

A_1	**Height of Dam (m)** – the vertical distance from the lowest point on the general foundation to the top of the dam.	Score
	< 10	1
	10 – 30	3
	30 – 100	6
	> 100	10
A_2	**Crest Width (m)**	Score
	>15	1
	6-15	3
	3-6	6
	<3 (or with a parapet greater than 2m)	10
A_3	**Type of Dam**	Score
	Rockfill dam	4
	Earth dam	10
A_4	**Type of Foundation**	Score
	Rock	1
	Treated rock-15	2
	Moraine/clay	4
	Treated moraine	6
	Treated alluvium	8
	Alluvium	10
A_5	**Storage Capacity** ($10^6 m^3$) - volume of the reservoir contained by the dam.	Score
	< 1	1
	1 – 50	2
	50 – 1000	4
	1000 – 5000	6
	> 5000	10
A_6	**Type of filtration system**	Score
	Modern filtration?	1
	Vertical and horizontal drains	
	Piping resistant homogeneous fill?	
	Relief wells, toe drains, finger drains	
	No filtration	10
	Arithmetic mean of variable parameters (A) $A = \dfrac{A_1 + A_2 + A_3 + A_4 + A_5 + A_6}{6}$	
	Modified based on the following source: O.DASCAL,~G·Dam Safety Directorate, Hydro-Québec.	

Table B.2. Classification parameters for variables.

B_1	**Age of dam** - Years since the commissioning of the dam.	Score
	0 – 5	8
	5 – 15	7
	15 – 30	3
	30 – 50	2
	> 50	1
B_2	**Pool of Record** - As a percentage of Hydraulic Height	**Score**
	>95%	1
	75 - 95%	5
	50 - 75%	8
	> 50%	10
B_3	**Seismicity** - Speed (cm/s) - Seismic activity that can affect the dam site, expressed as peak displacement velocity of bedrock surface at the dam site.	Score
	< 4	1
	4 – 8	2
	8 – 16	6
	16 – 32	8
	> 32	10
B_4	**Reliability of Spillway** - Spillway capacity, operating condition of gates, reliability of the hoisting gear, redundant sources of power.	Score
	Satisfactory	1
	Unsatisfactory	10
B_5	**Monitoring Continuity at Dam** - Continuity of monitoring is critical for timely reaction to potential loadings and adverse conditions.	Score
	Daily shift	1
	Daily presence	4
	Automated instrumentation	6
	Intermittent presence	10
B_6	Normal Pool (as a percentage of maximum pool {height or capacity?})	Score
	Dry dam	1
	<50%	3
	50% - 75%	6
	> 90%	10
	Arithmetic mean of variable parameters (B) $$B = \frac{B_1 + B_2 + B_3 + B_4 + B_5 + B_6}{6}$$	
	Modified based on the following source: O.DASCAL,~G·Dam Safety Directorate, Hydro-Québec.	

Table B.3. Classification parameters for hazard potential.

C	**Life loss and property damage** (as a function of population density and farm and industrial development)		
	Hazard potential	**Area affected**	**Score**
	Minimal	Uninhabited and undeveloped area with few natural resources	1
	Significant	Occasionally inhabited territory, cultivated farmland	3
	Major	Rural development (less than 2000 inhabitants), small- and medium-size industries, some natural resource	5
	High	Rural and urban development (more than 2,000 inhabitants) medium-size to large industries, major natural resources.	8
	Very high	Major city (more than 100,000 inhabitants) major industries	10

Note:

a) The size of the area affected is determined from the results of dambreak analyses conducted in compliance with the standard "Dambreak floodwave studies"; the area affected equals the flooded area. When the results of such studies are not available, a pessimistic evaluation of the size of the flooded area is used.
b) The term "industry" includes electric power plants.

See Appendix A for further explanation of the classification parameters.

Modified based on the following source: O.DASCAL,~G·Dam Safety Directorate, Hydro-Québec.

DAM CLASSIFICATION FORM
RISK OF FAILURE AND HAZARD POTENTIAL

DISTRICT ____________________
PROJECT ____________________

1. NAME OF DAM ____________________ LOCATION ____________________
2. DATE OF COMMISSIONING ____________________
3. LAST CLASSIFICATION DATE ________ CLASS ____________________
4. CHANGES SINCE THE LAST CLASSIFICATION ____________________

____

____

5. CLASSIFICATION PARAMETERS (current conditions)

A) Physical constants

A_1 – Height ____________ m	A_2 – Type of dam ____________
A_3 – Type of foundation ____________	A_4 – Storage capacity ____________ $10^6 m^3$
A_2 – Crest width ____________ m	A_6 – Type of filtration ____________

B) Variables

B_1 – Age ____________ years	B_2 – Seismicity (speed) ____________ cm/s
B_3 – Reliability of Spillway ____________	B_4 – Monitoring continuity ____________
B_2 – Pool History ____________ % of max	B_6 – Normal Pool ____________ % of max

C) Hazard potential parameter

C – Hazard potential ____________________
Dam breach analysis: Reference ____________________

6. SCORES

A_1 ____________	B_1 ____________
A_3 ____________	B_3 ____________
A_4 ____________	B_4 ____________
A_5 ____________	B_5 ____________
____________ /4 = ____________ = A	____________ /4 = ____________ = B

C = ____________

Vulnerability V = A + B = ____________ Overall score S = (V + 3C) / 50 = ____________

Classified by	Officer responsible for surveillance	Enter in dam log
Signature ____________	Signature ____________	Signature ____________
Name ____________	Name ____________	Name ____________
Date ____________	Date ____________	Date ____________

Figure B.1. Dam classification form.

DAM CLASSIFICATION FORM
RISK OF FAILURE AND HAZARD POTENTIAL

DISTRICT Ft. Worth
PROJECT ´Lewisville

1. NAME OF DAM Lewisville D LOCATION Lewisville, TX
2. DATE OF COMMISSIONING ______
3. LAST CLASSIFICATION DATE ______ CLASS ______
4. CHANGES SINCE THE LAST CLASSIFICATION ______

5. CLASSIFICATION PARAMETERS (current conditions)

D) Physical constants

A_1 – Height ______ m
A_2 – Type of dam Earth
A_3 – Type of foundation Alluvium
A_4 – Storage capacity 2205 $10^6 m^3$
A_2 – Crest width ______ m
A_6 – Type of filtration ______

E) Variables

B_1 – Age 35 years
B_2 – Seismicity (speed) none cm/s
B_3 – Reliability of Spillway good
B_4 – Monitoring continuity shift
B_2 – Pool History ______ % of max
B_6 – Normal Pool ______ % of max

F) Hazard potential parameter

C – Hazard potential Very High
Dam breach analysis: Reference ______

6. SCORES

A_1 6
A_3 10
A_4 10
A_5 6
32 /4 = 8 = A

B_1 2
B_3 1
B_4 1
B_5 1
5 /4 = 1.25 = B

C = 10

Vulnerability V = A + B = 9.25 Overall score S = (V + 3C) / 50 = 0.785

Classified by	Officer responsible for surveillance	Enter in dam log
Signature______	Signature______	Signature______
Name______	Name______	Name______
Date______	Date______	Date______

Figure B.2. Classification form completed for Lewisville Dam.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1999	Final

4. TITLE AND SUBTITLE
REMR Management Systems — Flood Control Structures:
Condition Rating Procedures for Earth and Rockfill Embankment Dams

5. FUNDING NUMBERS
32672

6. AUTHOR(S)
Glen Andersen, Luc Chouinard, and Stuart Foltz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratory (CERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PEFORMING ORGANIZATION REPORT NUMBER
TR REMR-OM-25

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, U.S. Army Corps of Engineers
20 Massachusetts Ave., NW
Washington, DC 20314-1000

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

9. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5385 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

For USACE civil works, the emphasis has been steadily shifting from construction of new facilities to maintenance and repair (M&R) of existing ones, so M&R has become an increasingly important part of the budget. In addition, USACE is one of many Federal agencies facing increasingly restrictive budgets and greater demands for budget justification. A prioritization system can be useful in the decision process for the management of existing facilities.

The objective of this project was to develop a rating procedure that describes the current condition of embankment dams in a uniform manner. The project also produced a procedure for the prioritization of M&R activities on embankment dams. A condition indexing (CI) approach was adopted in a manner similar to other CI systems that have been developed by CERL. A system approach to condition assessment was adopted wherein complex considerations were treated in a systematic manner.

Throughout this project, it was maintained that the resulting procedure would be applicable to the ranking of current M&R activities that can be programmed and funded within a normal budgetary cycle. Although this process may be used to evaluate actions deemed too urgent to wait for the normal budget cycle, this methodology is not applicable to actions of an emergency nature.

14. SUBJECT TERMS
REMR Management System
Civil Works
maintenance & repair
flood control
condition rating

15. NUMBER OF PAGES
108

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102